



A QUANTITATIVE FEEDBACK THEORY FCS DESIGN
FOR THE SUBSONIC ENVELOPE OF THE VISTA F-16
INCLUDING CONFIGURATION VARIATION AND
AERODYNAMIC CONTROL EFFECTOR FAILURES

THESIS

Vincent J. Cacciatore
2nd Lieutenant, USAF

AFIT/GE/ENG/95D-04

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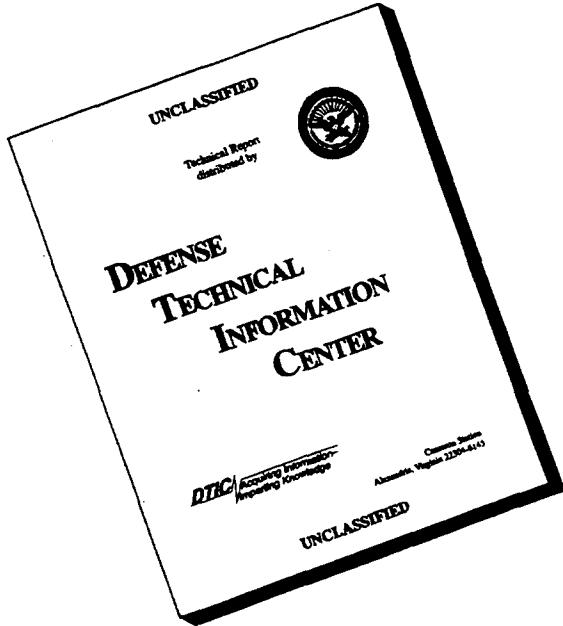
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2nd Lieutenant, USAF

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Vincent J. Cacciatore, B.S. Electrical Engineering
2nd Lieutenant, USAF

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Finally, I dedicate this thesis, consisting of some 225 pages and well over 1400 hours of blinding work, to Kimberley Michelle Wall for her patience, understanding, and love that enabled me to see through the delirium and remain focused on my priorities. I leave you with this excerpt from a poem that Kimberley gave me and that epitomizes my AFIT experience:

*If you want a thing bad enough
To go out and fight for it
Work day and night for it
Give up you time and your peace
and your sleep for it
. . . Then you'll get it!
(Success-Berton Bailey)*

Vincent J. Caciatoe

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| G QFT Compensator | 2-1 |
| T_R Tracking Control Ratio | 2-1 |
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| q_{ij} Reciprocal of Effective Plant Elements | 2-13 |

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| rps radians per second | 2-15 |
| ω_ϕ Phase Margin Frequency | 2-15 |
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Abstract

Fault tolerant flight control systems for combat aircraft are an alternative to excessively redundant aircraft designs or reconfigurable control laws. However, due to the range of flight conditions within a combat aircraft's operational flight envelope, the variety of its configurations, and the unavailability of an aerodynamic data base for damaged aircraft, designing fault tolerant systems is a complicated endeavor. Quantitative Feedback Theory is a robust control design technique especially well suited to manage the structured parametric uncertainty inherent in this problem, and consequently is applied as the primary design tool for this research. Furthermore, realistic failure models are developed for the VISTA F-16 and physical saturation constraints are applied to the control effectors. The ensuing fault tolerant design is subjected to realistic control inputs and validated with the applicable MILSTD specifications.

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INCLUDING CONFIGURATION VARIATION AND
AERODYNAMIC CONTROL EFFECTOR FAILURES

I. Introduction

With twenty percent of aircraft losses in combat and a significant percentage of aircraft losses in peacetime attributed to flight control system failures, the justification for designing fault tolerant control systems becomes apparent [18]. However until recent innovations in Self-Repairing Flight Control concepts, redundancy was the only design technique employed to manage such failures [18]. This brute force dependence on redundancy increased the weight, complexity and expense of combat aircraft while consequently reducing their payload, range, and operational effectiveness [13]. Self-Repairing Flight Control (SRFC) concepts, such as integrated components, drop in modules, autonomous maintenance diagnostics, and ultimately, fault tolerant flight control laws, significantly increased combat aircraft availability while also reducing the cost of acquiring and maintaining the aircraft [18], viz, life cycle cost.

Fault Tolerant Flight Control Laws have certain advantages over their conventional counterparts. Fault tolerant control systems do not require excessive redundancy and control effector overdesign, while affording enhanced stability margins. In essence, the fault tolerant flight control system transfers dependence on any particular control surface to the entire aircraft system. If an actuator and primary control surface fail, control authority may be maintained by utilizing the aircraft's healthy control surfaces or thrust vectoring capabilities, if applicable. Thus, the additional weight of possibly quadraplex replication of essential flight control elements is mitigated. Also, designers often increase the size of a control surface to account for battle damage losses [4]. Since this loss of control authority is an anticipated flight scenario in a fault tolerant design, airframe designers

can confidently reduce control surface overdesign without compromising the pilot's safety. Finally as an additional enhancement, fault tolerant flight control systems are designed to provide adequate stability in a variety of failure conditions so that the pilot can either continue the mission or in the worst case, safely bail out. The benefits to the Air Force in designing such a control law are evident. By employing fault tolerant flight control systems, there will be a reduction in casualties, weight and maintenance while providing increased performance, survivability, and affordability.

Just as there are a variety of approaches to effectively develop a self-repairing aircraft, there are an equal number of strategies proposed to design a fault tolerant flight control law. However there are several factors that make Quantitative Feedback Theory (QFT) the chosen method of design. First, QFT is a robust control technique that, unlike other design approaches, accounts for wide variations in structured plant parameter uncertainty.[9][10] Second, from the frequency template graphics generated in QFT, an engineer is able to discern whether the design can be accomplished by a single controller or whether gain scheduling will be necessary. Third, one of QFT's most salient features is that it enables the designer to input performance specifications at the beginning of the design process. By adding these specifications early in the process, intelligent decisions can be made to reduce the number of design iterations necessary to achieve an acceptable design. Finally, though fault detection and isolation schemes have been found to successfully manage failure cases, these approaches require a significantly robust system to provide reliable information.[8]. The compensators generated via the QFT technique insure this robustness. Therefore, due to Quantitative Feedback Theory's ability to handle wide variations in plant uncertainty, the graphical tools employed in the technique, and the introduction of performance specifications at the onset of the design, QFT is selected as the primary design tool.

1.1 Problem

The main objective of this research is to design a robust Flight Control System (FCS) using QFT which is tolerant to flight control effector damage from the outset. Specifically, this FCS is designed to be robust enough to provide nominal flight control

for the healthy aircraft, while providing stabilization for the aircraft with damaged control effectors. In addition to the primary objective, it is also the purpose of this research to systematically determine the maximum control effector damage that the proposed QFT design can accommodate.

1.2 Summary of Current Literature

1.2.1 Quantitative Feedback Theory Research. The United States Air Force through the Wright Laboratory Flight Dynamics Directorate Control Techniques Branch (WL/FIGS) and in affiliation with the graduate program at the Air Force Institute of Technology, has been a proponent of QFT since the early 1980's.[7] In that time, and due largely to the collaboration of Dr. Constantine Houpis and Dr. Issac Horowitz, the "father" of QFT, WL/FIGS has sponsored over 25 QFT driven flight control masters theses. The most current research in the area of full envelope flight control employing QFT was conducted by Lieutenant Odel Reynolds in 1993 [16] and Major Scott Phillips in 1994 [15].

Reynolds presented the first full subsonic envelope flight control system using QFT in his 1993 masters thesis. Previously, Quantitative Feedback Theory's mathematically rigorous nature limited its applicability as a control design technique. Without a computer design program to manage the numerous calculations involved in applying the theory, only designs with appropriately limited scopes were undertaken. However, in 1992 Richard Sating developed the first Quantitative Feedback Theory CAD package using *Mathematica* [19], and future generations of QFT designers were empowered to tackle more involved flight control problems. Lieutenant Reynolds used this increased capability to successfully design a flight control system for the VISTA F-16, incorporating the entire subsonic envelope in his design. This successful design enhanced the prominence of QFT as a robust control theory, and cleared the way for future full envelope FCS designs.

Phillips further demonstrated the capabilities of QFT by expanding Reynold's operational flight envelope through increased plant parameter variation, i.e., adding different external fuel tank configurations to the aircraft. Adding these variations enlarged the total number of plants by a factor of 4, resulting in a QFT design that would have been im-

possible before Sating's QFTCAD program. Not only was Phillips able to show that QFT could handle such a wide variation in parametric uncertainty, but as an experienced F-16 pilot, he was able to combine pilot preference and engineering expertise in the selection and blending of feedback variables. His selection of feedback variables and the inclusion of additional actuator rate and deflection saturation nonlinearities, allowed Phillips to construct a flight control system that was capable of meeting Level 1 flying qualities as dictated by the MILSTD 1797A [1] while simultaneously satisfying real world constraints. Finally, Phillips' analog design was transformed into the discrete domain and loaded into the Simulation Rapid Prototyping Facility [3] for further testing and evaluation. The next step, which Captain Pete Eide is currently developing at WL/FIGS, is to load Phillips' QFT based controller aboard the VISTA F-16 for man-in-the-loop flight tests. The first phase of these simulations evaluate the stability of Phillips' design, and the initial results have been very positive.

1.2.2 Failure Modeling. The quality and reliability of a QFT based design is heavily dependent on the accuracy of the plant models employed in its design. However, as a general rule, control engineers are not supplied with all the data necessary to model control surface failures exactly.[18] Aerodynamic data obtained from wind tunnel tests usually do not include a "rubber aircraft,"[14] where failures can be simulated by removal of aerodynamic surfaces. If engineers were given this data, the difficulty of modeling realistic failures would be greatly reduced. Due primarily to this limitation, and the inability of computer programs to employ this failure data in their simulation algorithms, previous fault tolerant flight control designs have modeled aerodynamic control surface failures as mere actuator failures. By handling failures in this way, designers are able to avoid modeling the effects of failures on the aircraft's dynamics. In other words, by modeling battle damage as actuator failures, engineers willfully disregard the warranted changes in the aircraft's stability derivatives. From a state-space viewpoint, this approach results in either "zeroing out" [12] or scaling the B matrix. Though modeling damage as actuator failures proves to be sufficient for other types of control problems [12], for a realistic evaluation of the effects of battle damage on an aircraft's control system this type of modeling is inadequate.

A more realistic approach was presented by Captain Mark S. Keating in his 1993 QFT MS thesis. Captain Keating was able to formulate the equations necessary to model control effector failures on the dynamics of an aircraft assuming asymmetric control surface damage. Though Keating's effort focussed on an unmanned research vehicle, his equations can be adapted to accommodate any airframe. In addition to modeling the change in dynamics caused by control effector failures, Keating also applied an external disturbance to account for the inherent cross-coupling of the lateral/directional and longitudinal aircraft channels. By modeling this coupling simply as an equivalent disturbance input into the system, Keating was able to maintain separation of the lateral/directional and longitudinal channels. This was a dramatic improvement on past failure designs because it realistically modeled battle damage and enabled the designer to reduce the complexity of the design.

1.3 Assumptions

It is assumed that the linear time invariant models (LTI) generated by Phillips accurately represent the VISTA F-16 through the entire subsonic flight envelope. In generation of these models the following assumptions are made:

1. Time spans of interest are short, ranging from 3 to 5 seconds in duration.
2. The aircraft is assumed a rigid body(assuming bending modes are not excited).
3. The reference coordinate system is fixed to the body of the aircraft and centered at the aircraft center of mass.
4. The earth is an inertial reference, and the atmosphere is fixed with respect to the earth, which is valid because the gyros and accelerometers used for control systems are incapable of sensing the angular velocity and acceleration of the earth.
5. The mass of the aircraft is constant.
6. Quasisteady flow is assumed, thus all derivatives with respect to velocity rates of change and unsteady aerodynamics are neglected.
7. The aircraft is symmetric about the XZ plane.

8. High amplitude command inputs and aircraft responses do not invalidate the assumed linear model.

Additional assumptions are:

1. Phillips' models represent the maximum uncertainty inherent in the healthy aircraft with configuration variation.
2. Aircraft orientation and velocity measurements are available.

1.4 Scope

The scope of this thesis includes compensator and prefilter designs for both the longitudinal and lateral/directional aircraft channels. The longitudinal design is strictly a MISO structure with single control surface failures, while the lateral/directional FCS is a 2X2 MIMO control system involving single, double, and triple control surface failures. In addition to the failure conditions imposed on the flight control design, rate and actuator saturation nonlinearities are included to simulate real world physical constraints. Success of the design is determined by meeting the MIL STD 1797A Level 1 flying qualities for the healthy aircraft and Level 2 or 3 for the failed aircraft.

1.5 Standards

The primary source of flying qualities specifications is the MILSTD 1797A.

1.6 Approach/Methodology

1. Employ the Simulation/Rapid-Prototyping Facility (SRF) [3] to generate the healthy aircraft models for the entire subsonic envelope of the VISTA F-16 including configuration variation. These models have been developed previously in Phillip's thesis [15] and need only to be validated for use in this design.
2. Simulate various levels of control effector damage by individually altering the healthy plant model stability and control derivatives. A similar failure modeling process was developed in Keating's thesis [11] and is adapted to fit the VISTA airframe.

3. Include single failures for the longitudinal channel and multiple failure cases in the lateral/directional channel where multiple control effectors are present. The entire test matrix can be found on Table 1.1.

| Types of Failures | Longitudinal | | Lat/Directional | |
|-------------------|--------------|-----------|-----------------|----------|
| | Elevator | Diff Tail | Rudder | Ailerons |
| No Failures | Healthy | Healthy | Healthy | Healthy |
| Single Failures | Fail 15% | Fail 25% | H ¹ | H |
| | Fail 25% | Fail 45% | H | H |
| | H | H | Fail 25% | H |
| | H | H | Fail 45% | H |
| | H | H | H | Fail 25% |
| | H | H | H | Fail 45% |
| Multiple Failures | H | Fail 25% | Fail 25% | H |
| | H | Fail 25% | H | Fail 25% |
| | H | H | Fail 25% | Fail 25% |
| | H | Fail 25% | Fail 25% | Fail 25% |
| | H | Fail 45% | Fail 45% | H |
| | H | Fail 45% | H | Fail 45% |
| | H | H | Fail 45% | Fail 45% |
| | H | Fail 45% | Fail 45% | Fail 45% |

Table 1.1 Test Matrix

4. Accommodating all of the plants listed in the test matrix, and utilizing the QFT design technique, construct a compensator (or digital controller) able to meet Level 1, 2 or 3 flying qualities depending on the condition of the aircraft.
5. Simulate the design in *Matlab*, driving the basic aircraft system with a maximum command gradient, and including realistic control effector saturation limitations. These simulations involve subjecting the compensated closed loop system to a step command input and evaluating the aircraft response. If the step response satisfies the MILSTD 1797A flying qualities specifications then the design is complete; if the system does not meet these specifications then it may be necessary to repeat step 4. Unfortunately, unless a routine, that incorporates changes in the aircraft dynamics

¹Represents Healthy Aircraft

due to control effector failures can be added to the existing SRF simulator, full non linear simulations will be unavailable to validate this design.

1.7 Organization

Chapter *II* overviews the Quantitative Feedback Theory MISO and MIMO design procedures and the specific design guidelines. The VISTA F-16 model is examined in Chapter *III*, and the failure modeling process is detailed in Chapter *IV*. The first four chapters cover the problem definition and setup, while Chapters *V* and *VI* explain the actual longitudinal and lateral/directional designs. The final designs as well as conclusions and recommendations provide closure in Chapter *VII*.

1.8 Materials, Data and Equipment

Phillips' linear time invariant (LTI) models are essential to the satisfactory completion of this thesis. No special equipment is required in this design other than a SPARC station 2 or greater and accompanying *Matlab*, MIMO QFTCAD, LATEX, and SunOS software.

1.9 Other Support

Dr. Meir Pachter, Dr. Constantine H. Houpis, and Major Dean Schneider serve on the thesis committee and Captain Peter Eide serves as the Air Force sponsor for this project. Dr. Pachter and Dr. Houpis are the committee co-chairman.

II. Design Methodology

This chapter outlines the basics of Quantitative Feedback Theory[9], the time simulations and specific guidelines used in the design.

Quantitative Feedback Theory (QFT) is a two degree of freedom frequency domain robust control design technique that emphasizes the use of feedback to achieve particular system tolerances despite plant uncertainty and cross-coupling effects.[5] The essence of a QFT design is to insure that a system's tracking and cross-coupling responses are members of a set of desired responses through the development of a single set of minimal-order compensators, the prefilter (F) and compensator (G). The details of a MISO (Multiple-Input Single-Output) QFT design are presented followed by an overview of the MIMO (Multiple-Input Multiple-Output) case. Finally, to adequately focus this discussion, it is anticipated that the reader has a basic understanding of the fundamentals of conventional control theory.

2.1 MISO QFT Design

2.1.1 Structure. The basic QFT structure shown in Fig. 2.1 is a unity feedback system with the plant (P) and the compensator (G) in cascade and the prefilter (F) in series with the closed loop. Given this structure, the control ratios for tracking T_R and disturbance rejection T_D are developed in Eqs. (2.1) and (2.2).

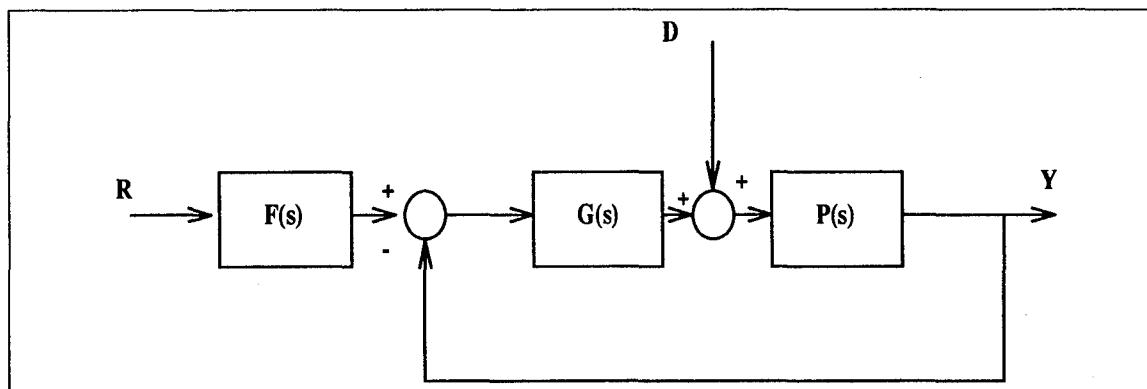


Figure 2.1 MISO QFT Design Structure

$$T_R(s) = \frac{Y(s)}{R(s)} = \frac{F(s)G(s)P(s)}{1 + G(s)P(s)} = \frac{F(s)L(s)}{1 + L(s)} \quad (2.1)$$

$$T_D(s) = \frac{Y(s)}{D(s)} = \frac{P(s)}{1 + G(s)P(s)} = \frac{P(s)}{1 + L(s)} \quad (2.2)$$

Where $L(s) = G(s)P(s)$ is the loop transmission function.

2.1.2 Plant Uncertainty. In this specific flight control design, the longitudinal channel is a 1x1 system, and the plant $P(s)$ from Fig. 2.1 represents the Laplace transform of the aircraft's longitudinal differential equations of motion. In general, the inputs to an aircraft plant are the control effectors (the stabilator, rudder and aileron deflections), and the outputs of the system are the aircraft states (position, velocity and acceleration). The coefficients of the aircraft differential equations are the stability and control derivatives. These derivatives are dependent on numerous factors. The most prominent of these factors are altitude, airspeed, aircraft center of gravity, and of particular interest in this design, aerodynamic control effector failures.

An aircraft, in normal operation, transitions through a range of altitudes, and airspeeds within its flight envelope represented by the X's in Fig. 2.2. In addition to the changes in altitude and airspeed the aircraft can also experience possible aerodynamic control effector failures, and different CG locations due to external stores or fuel consumption. These varying CG positions and failures add two additional dimensions to the flight envelope such that an aircraft flying at 10,000 feet, Mach .4 ,with 2 external fuel tanks, and 45% rudder failure is represented by a unique set of stability and control derivatives in this design. Each of these factors which influences an aircraft's control response, can only be anticipated by the designer *a priori*. Therefore, the parametric uncertainty, or more particularly, structured plant parameter uncertainty confronts the aircraft controls designer. In a robust control design, such as QFT, this structured uncertainty must be defined or at least bounded in order to proceed with the design process. In a QFT design this quantification of parameter uncertainty is accomplished via frequency templates.

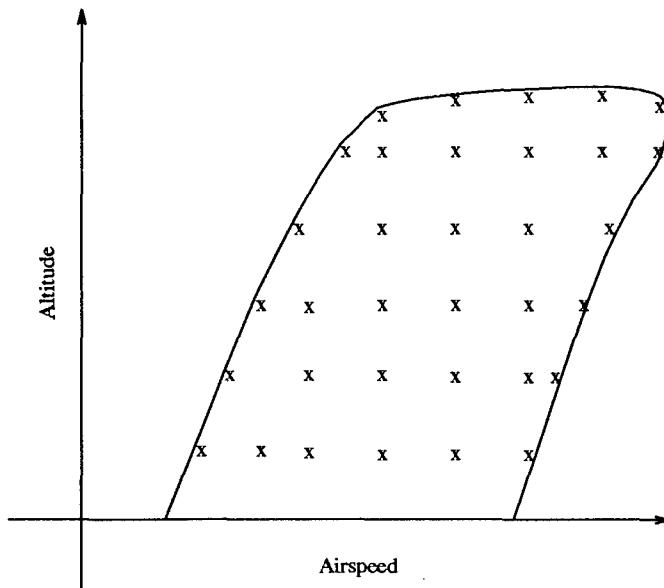


Figure 2.2 Typical Flight Envelope

2.1.3 Frequency Templates. QFT frequency templates are the graphical interpretation of the quantified design uncertainty. They are formed in two distinct steps. First, transfer function matrices (P_j) are generated over the entire range of possible plant configurations discussed in the previous section, where each transfer function comprises one plant in the design set \mathcal{P} . The exact number of plants needed to define the parameter space is highly dependent on the specific design problem, however the goal in any design is to accurately define the space with the minimum number of plants. The greater the number of plants the more exactly the uncertainty is quantified, but with an increasing number of plants the computation burden becomes inhibiting. Finally, the frequency response of each J plant is generated, and then mapped onto a two dimensional graph representing the relative magnitude and phase at a particular frequency. The resulting graph, or frequency template, displays the uncertainty inherent in the design.

Figure 2.3 illustrates an example of a QFT frequency template, where the X's represent specific plants. Frequency templates enable the designer to see patterns otherwise obscured in the transfer function data. If the plants are widely dispersed on the frequency templates, then some additional configurations must be evaluated to further resolve the uncertainty. If there is a tight group of points within one region and only a few cases an

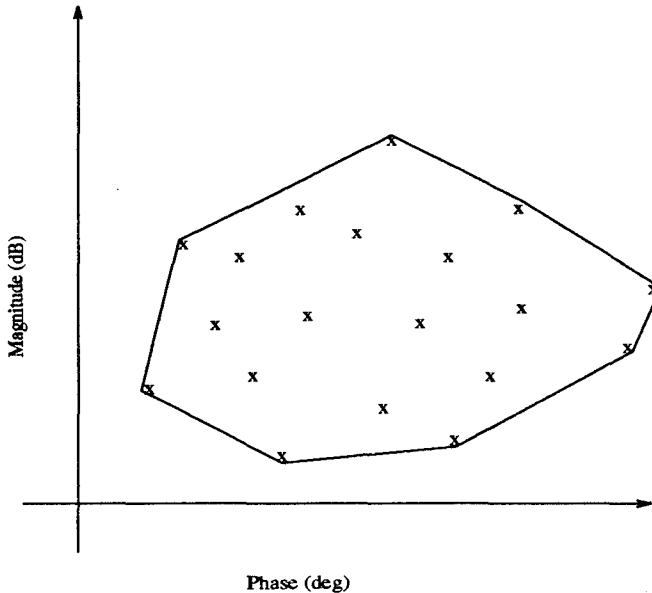


Figure 2.3 QFT Frequency Template $TP_e(j\omega_i)$ for some $\omega = \omega_i$

extended distance apart, then those “rebel” plant cases must be investigated. It is possible that those plant cases represent some unfeasible physical configuration, or are simply too problematic to include in the design set. The information content of the frequency templates is extensive, and the feedback to the designer is immediate and dramatic. Important decisions, such as whether to keep those rebel plants, divide the design into two “compensator scheduled” systems, or add plant cases to the design set, can be made intelligently at this point in the design. This ability to graphically examine the uncertainty early in the design process is one of the ways in which the transparency of QFT is experienced by the designer.

2.1.4 Specifications. In addition to the frequency templates, the control system designer witnesses the transparency of QFT through the incorporation of closed-loop control system performance specifications at the beginning of the design process. After quantifying the uncertainty and constructing the frequency templates, the next step in the design procedure is to generate frequency domain tracking and disturbance models. An example of typical tracking models, T_{R_U} (upper bound) and T_{R_L} (lower bound), are shown in Fig. 2.4. These models form the boundaries of the desired tracking responses, also known as the thumbprint specifications, and are developed based on satisfying two

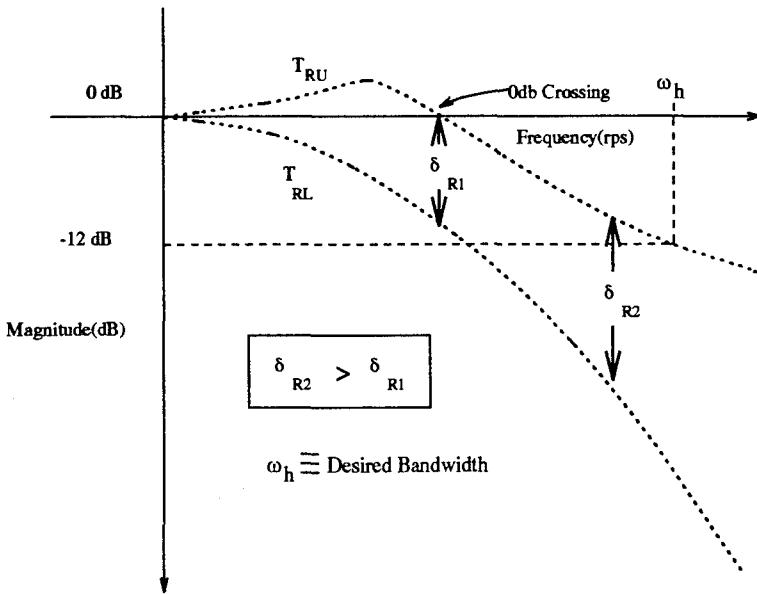


Figure 2.4 QFT Tracking Specifications

criteria. The boundaries must meet the desired second order step forcing function figures of merit for underdamped and overdamped responses, as well as the QFT requirement on the δ_R spread. Quantitative Feedback Theory requires that δ_R , or the magnitude difference between the upper and lower tracking models at a particular frequency, is monotonically increasing for frequencies above the 0 dB crossing frequency of T_{RU} . Finally, to satisfy the performance specifications the actual responses must lie within these boundaries at least for frequencies less than ω_h .

The external disturbance rejection specifications for a FCS design are typically modelled by a constant magnitude for all frequencies as shown in Fig. 2.5, and the stability specifications are expressed in terms of open loop phase and/or gain margins indicated on Fig. 2.6.

2.1.5 Nominal Plant Selection. Before QFT boundaries can be generated, a nominal plant must be selected. Selection of a nominal plant is highly dependent on a particular design but some guidelines are presented in the references.[5][7][9] Once selected the nominal plant (P_o) is the only plant employed for the remainder of the design. All of the boundaries and compensators are synthesized based on this nominal plant.

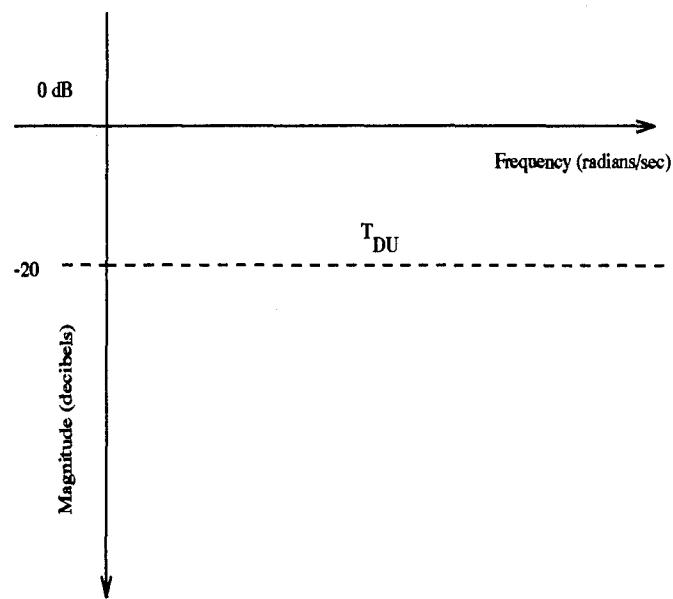


Figure 2.5 Disturbance Specification

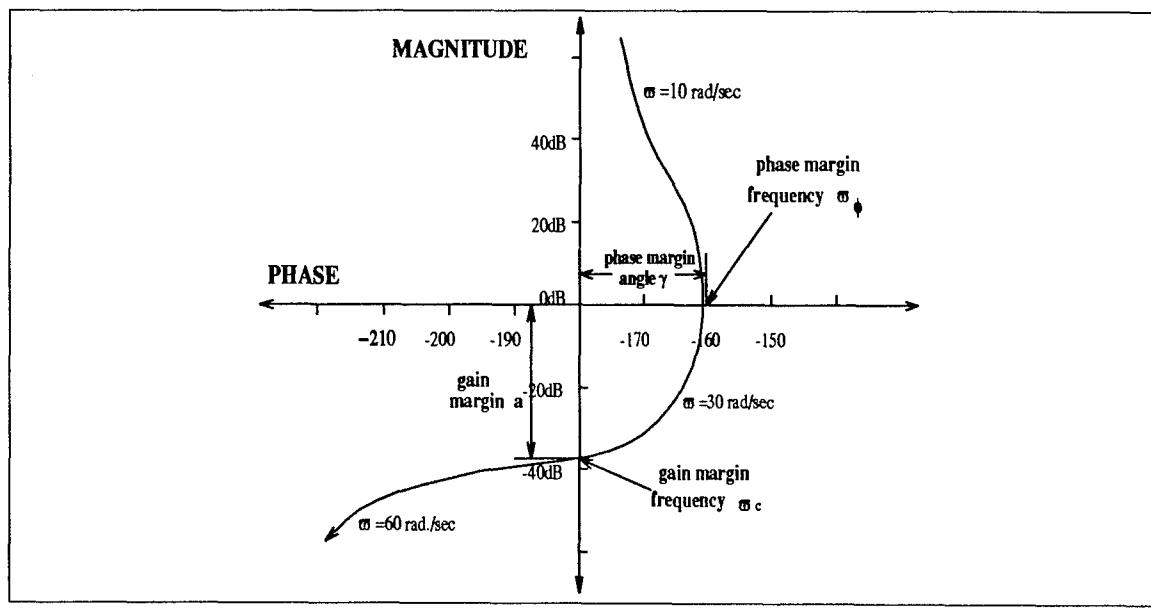


Figure 2.6 Gain Margin/Frequency and Phase Margin/Frequency Definitions

2.1.6 Nichols Chart QFT Boundaries. With the frequency templates, design specifications, and nominal plant selection developed in previous sections, the next step of a MISO QFT design is to generate the QFT stability, tracking, disturbance, and composite boundaries. The synthesis of QFT boundaries is a fairly involved process that is left for the references to explain in detail. Fortunately, the designer does not have to be overly concerned with the boundary generation, since the QFT CAD package completely automates this process. Once the frequency templates, and design specifications are loaded, the 'Bounds' option is selected and all of the Nichols chart frequency bounds are established. The tracking and disturbance boundaries ($B_R(j\omega)$ and $B_D(j\omega)$) are limits associated with particular frequencies plotted on the Nichols chart, and the stability boundaries ($B_S(j\omega)$) are contours encircling the 0 dB -180° point on the Nichols chart. Via QFT CAD, each of these boundaries can be viewed independently or combined in a composite boundary. The composite boundary ($B_o(j\omega)$) represents the most restrictive boundary at each frequency, where the most restrictive boundary requires the most gain to satisfy. Fig. 2.7 shows a sample set of QFT Nichols chart design boundaries. Notice that there is only one boundary for each frequency since this figure represents the composite QFT boundary. With all the boundaries synthesized the designer is now able to intelligently construct the QFT robust compensator G .

2.1.7 Loop Shaping - Synthesis of the QFT Compensator. The compensator G is synthesized by first mapping the nominal open-loop ($GP_o(s)$) frequency response onto the QFT Nichols chart with its associated stability, tracking, and disturbance boundaries. Poles, and zeros are added and modified along with the gain until the nominal loop meets the QFT composite boundaries. This process of modifying the compensator until the nominal open-loop satisfies the QFT boundaries is known as loop shaping. An example of QFT loop shaping is shown in Fig. 2.8, where the nominal loop wraps around the composite stability bound, or M_L contour, while maintaining a gain sufficient to clear, or be tangent to, each composite bound shown on the Nichols chart. If the nominal loop intersects the stability contour then a zero must be included to provide the necessary increase in phase to circumvent the contour. If the loop wraps around the M_L contour exactly but some of the composite boundaries are not satisfied then additional gain must be added and

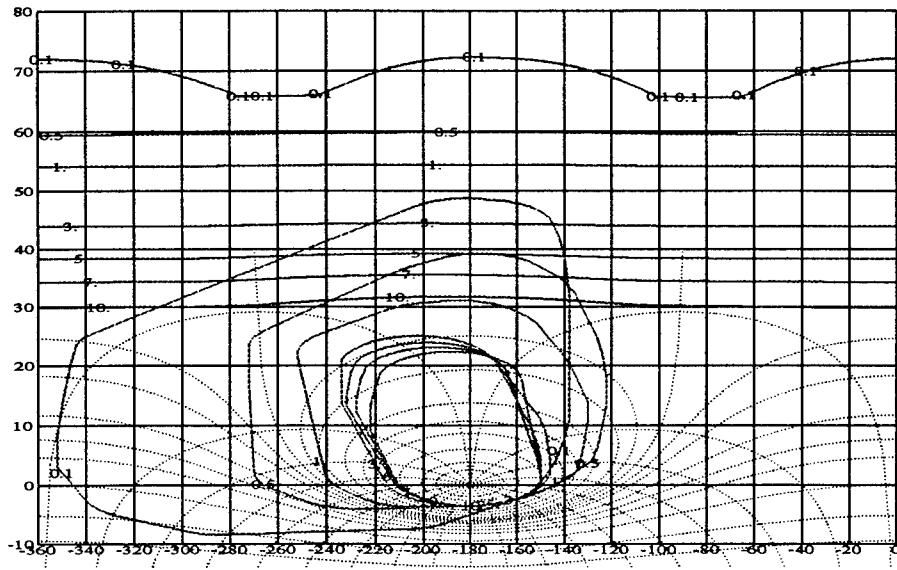


Figure 2.7 QFT Stability $B_S(j\omega)$ and Composite $B_o(j\omega)$ Bounds

the poles and zeros readjusted. This “trial and error” approach is performed with ease given the QFT CAD software. This software enables the designer to visualize the tradeoffs between increasing the gain and order of the compensator and meeting the required bounds. Since these tradeoffs are entirely graphical, the engineer can instantaneously determine whether the system meets specifications or whether further modifications are necessary. This instantaneous feedback to the designer dramatically reduces the number of design iterations required to successfully construct the robust compensator.

There are two additional concerns the designer faces while loop shaping. First, the system must be at least Type 1 to achieve zero steady-state error for a step input. Therefore, the compensator must include a pole at the origin if the chosen nominal plant is Type 0. Second, saturation may occur if the system gain is increased without reservation. Though it may be possible to satisfy the composite boundaries for all frequencies by consistently increasing this gain, the resulting compensator may not be implementable due to control surface rate or deflection saturation.

Meeting all the required QFT composite boundaries with the nominal loop transmission function insures that the system has the necessary robustness to guarantee that the closed-loop frequency response of all the plants lies between the upper and lower tracking

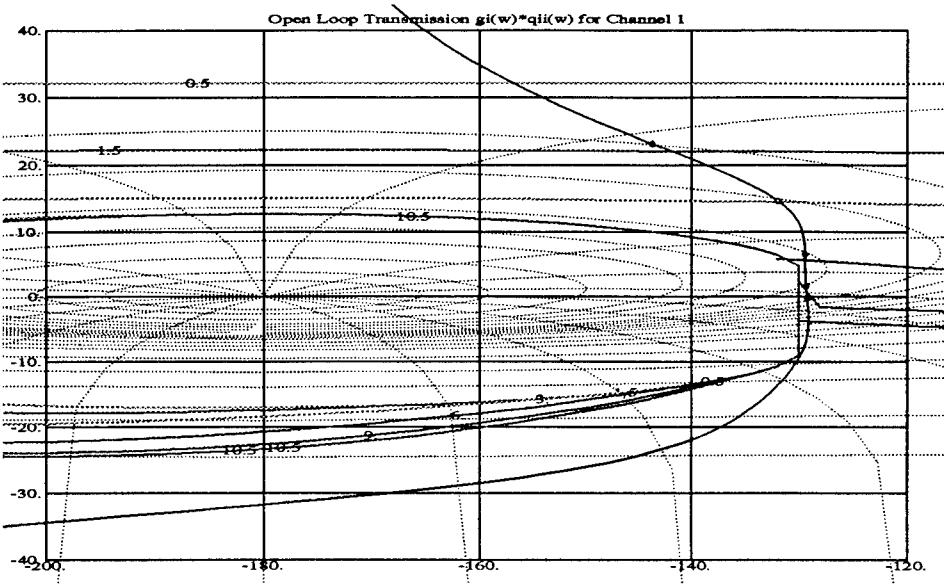


Figure 2.8 QFT Loop Shaping

models in Fig. 2.4, that the system can maintain the required stability margin, and that the system can reject a particular level of external disturbance. It is important to stress that if the nominal loop design satisfies the required QFT bounds then every plant used to synthesize the frequency templates also meets the established specifications. Use of the nominal plant is merely a way of reducing the complexity of the design.

2.1.8 Prefilter Design. As Fig. 2.9 illustrates, the compensator (\mathbf{G}) has provided the system with the required robustness to fit between the tracking models. This robustness, however, does not necessarily insure the system has the desired frequency response characteristics. It is the purpose of the prefilter (\mathbf{F}) to position the robust tracking response between the upper and lower tracking models as shown in Fig. 2.10. The resulting control ratio with the prefilter included is found in Eq. (2.3).

$$T_R = \frac{FGP}{1 + GP} \quad (2.3)$$

By positioning the closed-loop frequency response between T_{R_U} and T_{R_L} a successful MISO QFT design has been completed.

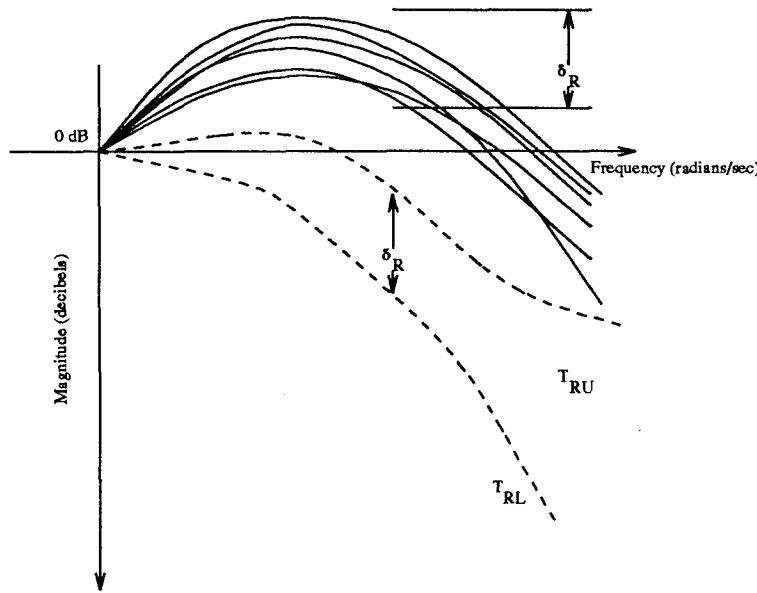


Figure 2.9 Compensated Closed-Loop Frequency Response without Prefilter

2.1.9 MISO Design Summary. Before examining the MIMO QFT case, it is helpful to briefly summarize the key features of the MISO development. The setup of the MISO design involves defining the unity gain feedback structure, identifying the region of structured plant parametric uncertainty, establishing the stability, tracking, and disturbance models, and generating the frequency templates. The templates allow the designer to visualize the uncertainty in the design and make some intelligent decisions including selection of the nominal plant. With this plant the QFT composite bounds are formed and the nominal loop is mapped onto the QFT Nichols chart. A compensator is then synthesized in the loop shaping process to clear the associated bounds on the Nichols chart. The last step in the MISO QFT design is to position the tracking responses within the upper and lower tracking models via the prefilter. Thus, a single compensator (\mathbf{G}) and prefilter (\mathbf{F}) is obtained, and a robust design over a specific region of parametric plant uncertainty is established. This technique contrasts to “point design” methods requiring a set of compensators to guarantee similar robustness.

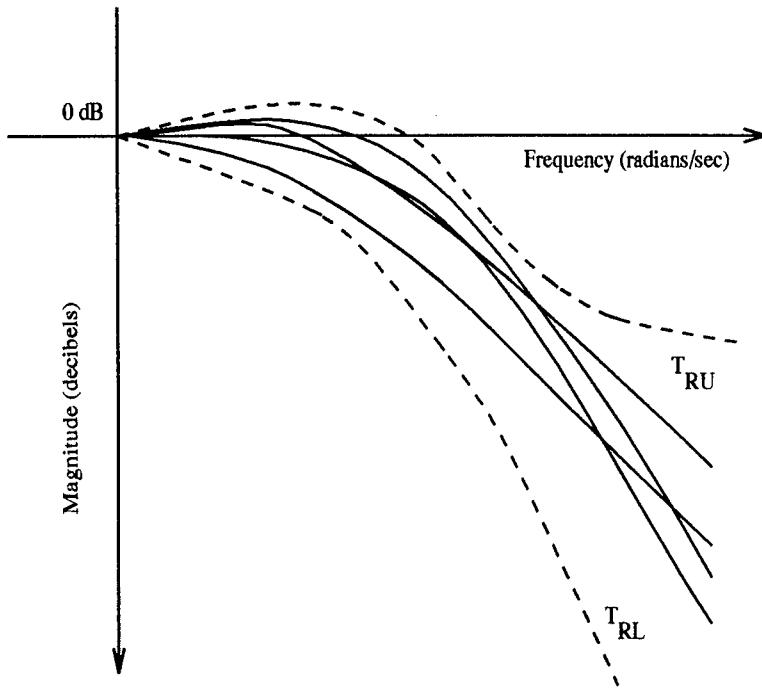


Figure 2.10 Compensated Closed-Loop Frequency Response with Prefilter

2.2 MIMO QFT Design

2.2.1 Structure. Figure 2.11 represents the general 2X2 QFT MIMO system including an external disturbance. The purpose of this system is to track a desired reference signal \mathbf{R} while rejecting the effects of the external disturbance \mathbf{D} on the output \mathbf{Y} . The corresponding matrices identified in this figure are:

$$\mathbf{F} = \begin{bmatrix} f_1 & 0 \\ 0 & f_2 \end{bmatrix} \quad \mathbf{G} = \begin{bmatrix} g_1 & 0 \\ 0 & g_2 \end{bmatrix} \quad \mathbf{P}_e = \begin{bmatrix} p_{e_{11}} & p_{e_{12}} \\ p_{e_{21}} & p_{e_{22}} \end{bmatrix} \quad \mathbf{P}_D = \begin{bmatrix} p_{d_{11}} \\ p_{d_{21}} \end{bmatrix} \quad (2.4)$$

where

$$\mathbf{P}_e = \mathbf{P}\mathbf{W} \quad (2.5)$$

Unlike the MISO case, solving the MIMO design problem found in Fig. 2.11 yields a complex closed form expression. By treating the MIMO case as m^2 equivalent MISO cases [9] the designer is able to circumvent this complex MIMO expression and focus on the more tractable mathematics associated with the MISO cases.

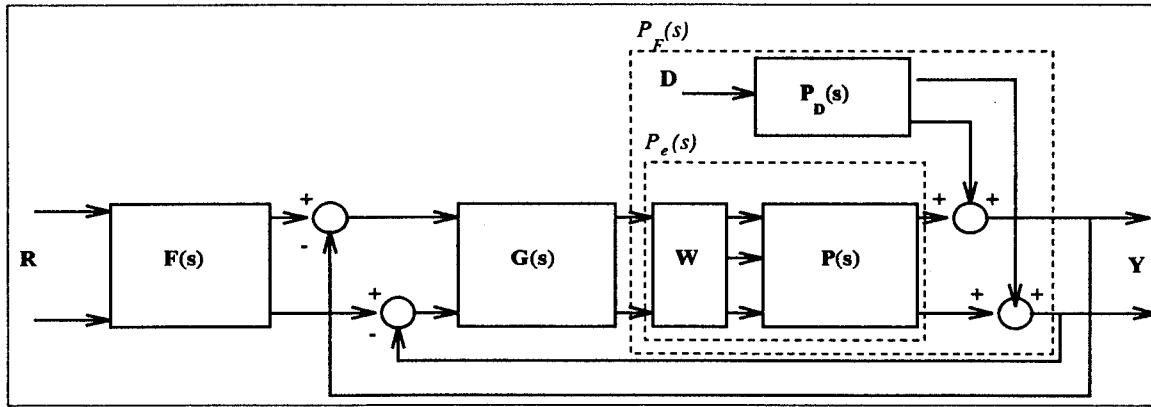


Figure 2.11 A 2X2 MIMO QFT Design Structure Including An External Disturbance

2.2.2 Weighting Matrix. A MIMO QFT design requirement is that the number of system inputs must equal the number of system outputs, in other words the plant must be square. To square the plant, a weighting matrix \mathbf{W} is introduced. In previous QFT research a connection between the level of uncertainty and the weighting matrix has been established. It has been found that a properly chosen weighting matrix can reduce the uncertainty and thus the difficulty of a QFT design. Additional details on the particular weighting matrix used in this design can be found in Chap. VI.

2.2.3 Diagonal Dominance. Diagonal dominance is yet another constraint on the MIMO QFT design. If the diagonal dominance condition for a 2x2 MIMO system given by:

$$p_{11}(j\omega)p_{22}(j\omega) > p_{12}(j\omega)p_{21}(j\omega) \quad (2.6)$$

as

$$\omega \rightarrow \infty.$$

is satisfied then a Method 1 QFT design can be applied, else a Method 2 design must be attempted. The specifics on these two types of QFT designs are thoroughly discussed in the references and are left for the interested reader to explore.[9]

2.2.4 MIMO Equivalence. For the 2x2 system encountered in this FCS design (Fig. 2.11) the MISO equivalent expressions are shown in Fig. 2.12. This equivalent scheme

assumes a diagonal compensator (**G**) and prefilter (**F**) found in Eq. 2.4. The control ratio for each diagonal MISO loop is given by

$$t_{ii} = \frac{f_{ii}g_iq_{ii} + d_{ii}q_{ii}}{1 + g_iq_{ii}} = t_{r_{ii}} + t_{d_{ii}} \quad (2.7)$$

$$t_{r_{ii}} = \frac{f_{ii}g_iq_{ii}}{1 + g_iq_{ii}} \quad t_{d_{ii}} = \frac{d_{ii}q_{ii}}{1 + g_iq_{ii}} \quad (2.8)$$

and the off-diagonal control ratios are:

$$t_{ij} = t_{d_{ij}} = \frac{d_{ij}q_{ii}}{1 + g_iq_{ii}} \quad i \neq j \quad (2.9)$$

The d_{ij} terms in Eqs. (2.8) and (2.9) represent both the external disturbance and cross-coupling disturbance inputs into the system. The relationship established in Eq. (2.10) was developed by Captain Dennis Trosen in his 1993 thesis to incorporate the external disturbance input into the MIMO equivalent MISO systems. [21]

$$d_{ij} = (d_{ext})_{ij} + c_{ij} \quad (2.10)$$

where

$$(d_{ext})_{ij} = \sum_{k=1}^x \left[\frac{p_{d_{kj}}}{q_{ik}} \right] \quad (2.11)$$

$$c_{ij} = - \sum_{k \neq i}^m \left[\frac{t_{kj}}{q_{ik}} \right] \quad (2.12)$$

Substituting Eqs. (2.11) and (2.12) into Eq. (2.10):

$$d_{ij} = \sum_{k=1}^x \left[\frac{p_{d_{kj}}}{q_{ik}} \right] - \sum_{k \neq i}^m \left[\frac{t_{kj}}{q_{ik}} \right] \quad (2.13)$$

Where x represents the number of disturbance inputs and m represents the dimension of the plant matrix (**P**). These disturbance inputs make the MISO cases truly equivalent to the MIMO system. As for the q_{ij} terms, they represent the reciprocals of the effective

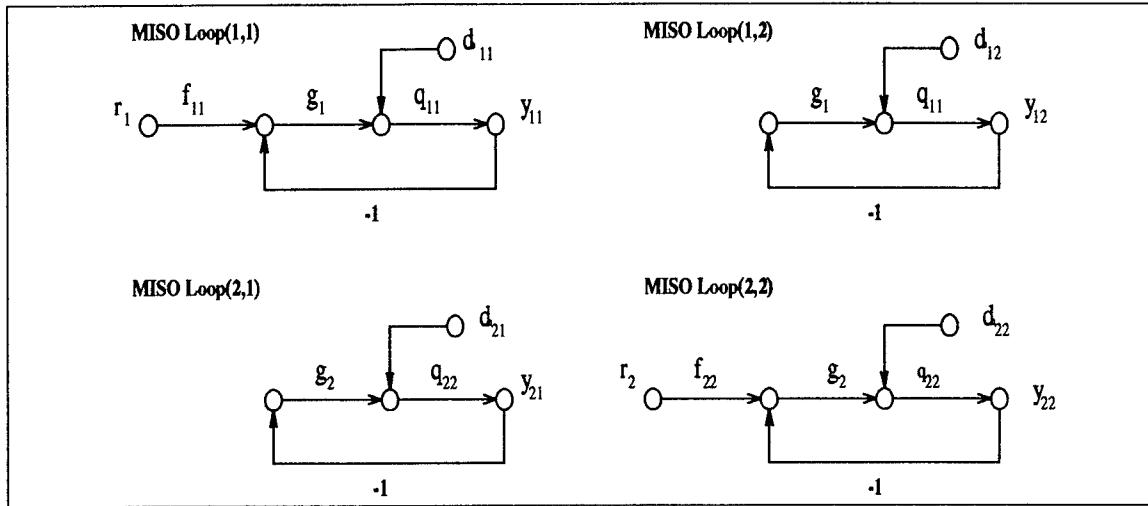


Figure 2.12 Equivalent MISO Loops for MIMO QFT Structure, with Diagonal F Matrix

plant elements. The origin of the q_{ij} terms is shown in Eqs. (2.14) and (2.15).

$$\mathbf{P}_e^{-1} = \begin{bmatrix} p_{e_{11}}^* & p_{e_{12}}^* \\ p_{e_{21}}^* & p_{e_{22}}^* \end{bmatrix} \quad (2.14)$$

$$\mathbf{Q} = \begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{bmatrix} = \begin{bmatrix} \frac{1}{p_{e_{11}}^*} & \frac{1}{p_{e_{12}}^*} \\ \frac{1}{p_{e_{21}}^*} & \frac{1}{p_{e_{22}}^*} \end{bmatrix} \quad (2.15)$$

For complete treatment of this equivalence between the MIMO and the m^2 cases the reader is directed to the references. [5] [8] [21]

Before examining the plant models in Chap. III some details concerning the time simulations and design guidelines need to be addressed.

2.3 Time simulations

The time simulations are achieved via the *Matlab* Runge Kutta 45 numerical integration routine and *Simulink*.[2][20] The step size is limited to 10^{-4} seconds, and the integrators are set with zero initial conditions. For the maximum command responses, rate and deflection saturation limits are incorporated in the design. These limits are imposed via *Simulink's Saturation* and *Rate Limiter* functions.

| Control Surface | Deflection Limit | Rate Limit |
|-------------------|------------------|----------------|
| Horizontal Tail | ± 20 degrees | 60 degrees/sec |
| Differential Tail | ± 7 degrees | 60 degrees/sec |
| Flaperons | ± 20 degrees | 60 degrees/sec |
| Rudder | ± 30 degrees | 60 degrees/sec |

Table 2.1 Control Surface Rate and Deflection Limits for the VISTA F-16

2.4 Design Guidelines

Some additional guidelines are:

1. The bandwidth of concern is 0.5 to 3.5 rps in agreement with previous research and the MILSTD 1797A that has established this frequency range as the pilot's bandwidth.
2. The bending modes for the VISTA are isolated to frequencies above 30 rps. Therefore it is essential that the phase margin frequency ω_ϕ is below 30 rps. In a QFT design this can be accomplished by locating the nominal plant at the highest (largest relative magnitude) point on the 30 rps frequency templates to insure a 30° phase margin for the rest of the design plants.
3. To facilitate transformation of this analog design to an actual digital Flight Control Computer (FCC) the poles and zeros of the controllers can not exceed 60 rps. This figure is calculated based on a 50 Hz sampling rate which is typical of a modern FCC.
4. Following Phillips' design, the compensator gain is limited by real world constraints such as rate and deflection saturation limits. The actual control surface saturation and rate limits for the VISTA F-16 can be found in Table 2.1.
5. To achieve the primary goal of this design, compensators are to be constructed for the longitudinal and lateral/directional channels that provide nominal flight control for the healthy aircraft and stabilization and debilitated performance for the failed cases. Satisfying these demands may require that the performance of the healthy aircraft is sacrificed to provide adequate robustness for the more severe failures. Ultimately the aircraft must be able to meet Level 1, 2 or 3 flying quality specifications for the failed aircraft and Level 1 or 2 for the healthy aircraft.

III. VISTA F-16 Aircraft Model

This chapter examines the modelling of the healthy VISTA (Variable In-flight Stability Test Aircraft) F-16, including the longitudinal, lateral/directional, and actuator models. Further information concerning control effector failure modeling follow in Chap. IV.

To quantify the parameter uncertainty involved in the subsonic flight envelope of the VISTA F-16 FCS design, which includes changes in the aircraft CG, linear time-invariant (LTI) aircraft models are generated that span the airspeed-altitude-CG parameter space. These aircraft models are used as the plants in the ensuing QFT design.

3.1 VISTA F-16

The two seat VISTA F-16 is a modification of the F-16D model, adding additional flight control components such as the variable stability flight control system (VSS), and the additional weight that can be attributed to these components. The VSS provides the evaluation pilot with the real flight motions, accelerations, and handling qualities he would feel if seated in the cockpit of a simulated aircraft [22]. The schematic of the VISTA and accompanying basic aircraft data can be found on Fig. 3.1 and on Table 3.1.

3.2 Flight Scenarios

As an extension of Phillips' work, this research includes the full subsonic envelope of the VISTA F-16 from 1,000 to 50,000 feet and from 0.2 to 0.8 Mach with the following configuration variations:

1. Clean(no external fuel tanks)

| Basic Data for VISTA F-16 | |
|---------------------------|--------------|
| Wing Area | 323.20 SQ FT |
| V Tail Area | 54.80 SQ FT |
| Rudder Area | 11.65 SQ FT |
| Aileron Area | 26.56 SQ FT |
| Stabilator Area | 63.70 SQ FT |

Table 3.1 Basic Aircraft Data

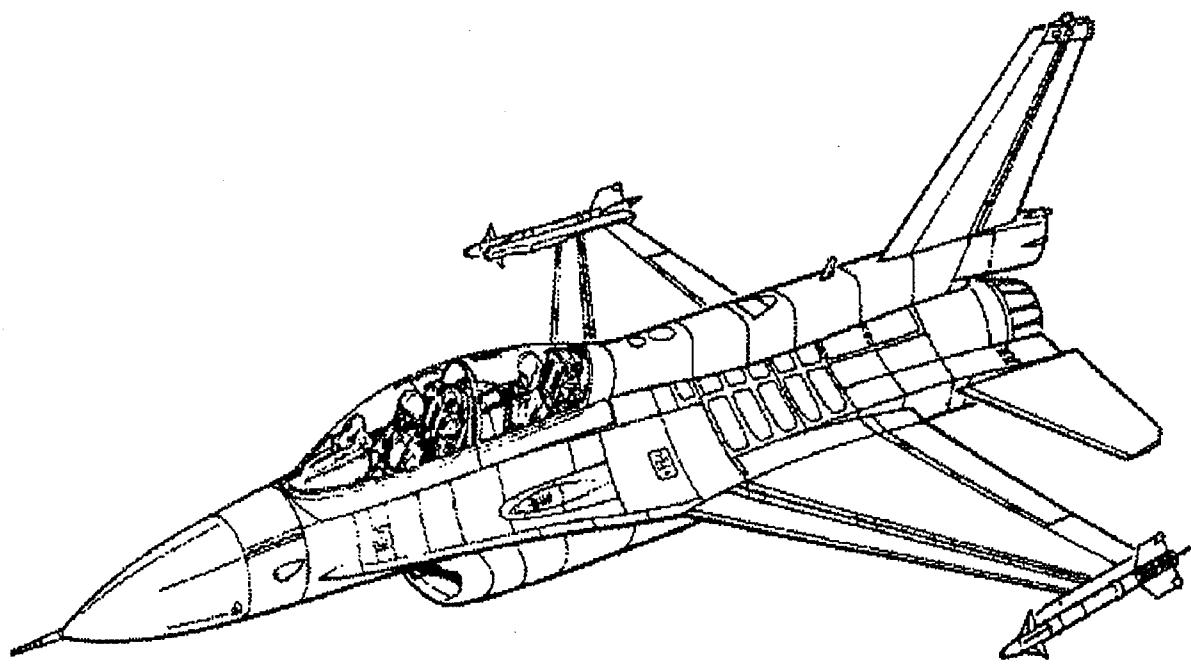


Figure 3.1 VISTA F-16

2. Centerline fuel tank
3. Two wing tanks

Phillips also included a three tank configuration at the beginning of his research but later abandoned this set up in lieu of generating a higher-order compensator to satisfy the increase in plant parameter uncertainty. Therefore, in this research the 3 tank configuration is also not included.

It is important to note that the LTI models originated from the Simulated Rapid Prototyping Facility(SRF) at WL/FIGS and that this program did not initialize at low airspeeds when loaded with certain tank configurations. This failure to initialize manifested as “strange behavior at the left edge of the flight envelope”[6] when Phillips’ design was loaded into the *Aviator* nonlinear simulator. Therefore the current design may also exhibit the similar behavior since the failure models are based on Phillips’ original 282 plants. More detailed information including procedures used by Reynolds and Phillips in determining SRF plants for the left side of the flight envelope can be found in the literature [16]. As an addition to the configuration variation introduced by Phillips, this research examines the effects of control effector failures. These failure cases are explained in Chap. IV.

3.3 LTI Aircraft Model Generation

The LTI aircraft models were generated by Major Phillips in his 1994 Thesis [15]. The SRF trims the aircraft at a selected altitude, airspeed and CG within its flight envelope, then linearizes the aircraft’s equations of motion about this selected operating point. In this process of linearizing the nonlinear aircraft equations of motion, the SRF utilizes a database of VISTA wind tunnel data to determine the stability derivatives in the form of state-space **A** and **B** matrices. The arrangement of the stability derivatives in the

| State | Units |
|----------|---------|
| θ | deg |
| u | ft/sec |
| α | deg |
| q | deg/sec |
| ϕ | deg |
| β | deg |
| p | deg/sec |
| r | deg/sec |

Table 3.2 Units of Aircraft Model States

state-space equation $\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$ is shown in Eq. 3.1.

$$\begin{bmatrix} \dot{\theta} \\ \dot{u} \\ \dot{\alpha} \\ \dot{q} \\ \dot{\phi} \\ \dot{\beta} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ X_\theta & X_u & X_\alpha & X_q & 0 & 0 & 0 & 0 \\ Z_\theta & Z_u & Z_\alpha & Z_q & 0 & 0 & 0 & 0 \\ M_\theta & M_u & M_\alpha & M_q & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & \phi_r \\ 0 & 0 & 0 & 0 & Y_\phi & Y_\beta & Y_p & Y_r \\ 0 & 0 & 0 & 0 & 0 & L_\beta & L_p & L_r \\ 0 & 0 & 0 & 0 & 0 & N_\beta & N_p & N_r \end{bmatrix} \begin{bmatrix} \theta \\ u \\ \alpha \\ q \\ \phi \\ \beta \\ p \\ r \end{bmatrix} \quad (3.1)$$

$$+ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ X_{\delta_{elev}} & 0 & X_{\delta_{flap}} & 0 & 0 \\ Z_{\delta_{elev}} & 0 & Z_{\delta_{flap}} & 0 & 0 \\ M_{\delta_{elev}} & 0 & M_{\delta_{flap}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & Y_{\delta_{dfail}} & 0 & Y_{\delta_{ail}} & Y_{\delta_{rud}} \\ 0 & L_{\delta_{dfail}} & 0 & L_{\delta_{ail}} & L_{\delta_{rud}} \\ 0 & N_{\delta_{dfail}} & 0 & N_{\delta_{ail}} & N_{\delta_{rud}} \end{bmatrix} \begin{bmatrix} \delta_{elev} \\ \delta_{dfail} \\ \delta_{flap} \\ \delta_{ail} \\ \delta_{rud} \end{bmatrix}$$

The units of each of the states listed in Eq. (3.1) are listed in Table 3.2. It is evident from this state-space representation that the longitudinal and lateral channels are considered

completely decoupled. This is consistent with the steady level trim conditions at which the plants are generated.

3.4 Longitudinal Aircraft Model

The state space longitudinal aircraft model extracted from Eq. (3.1) is

$$\begin{bmatrix} \dot{\theta} \\ \dot{u} \\ \dot{\alpha} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ X_\theta & X_u & X_\alpha & X_q \\ Z_\theta & Z_u & Z_\alpha & Z_q \\ M_\theta & M_u & M_\alpha & M_q \end{bmatrix} \begin{bmatrix} \theta \\ u \\ \alpha \\ q \end{bmatrix} + \begin{bmatrix} 0 \\ X_{\delta_{elev}} \\ Z_{\delta_{elev}} \\ M_{\delta_{elev}} \end{bmatrix} \begin{bmatrix} \delta_{elev} \end{bmatrix}. \quad (3.2)$$

The flap function of the F-16 flaperons is selected only during the takeoff and landing phases of flight. Since this design is only concerned with the MILSTD Category A nonterminal phase of flight, the δ_{flap} control input is eliminated.

Pilot control inputs are typically spaced no further apart than five seconds, so five seconds is accepted as an appropriate time period of interest in manual flight control system design. Due to the dominance of the short period mode in this time scale following a control input, the short period approximation is used in the longitudinal channel design process. The resulting short period approximation state-space model is shown in Eq. (3.3).

$$\begin{bmatrix} \dot{\alpha} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} Z_\alpha & Z_q \\ M_\alpha & M_q \end{bmatrix} \begin{bmatrix} \alpha \\ q \end{bmatrix} + \begin{bmatrix} Z_{\delta_{elev}} \\ M_{\delta_{elev}} \end{bmatrix} \begin{bmatrix} \delta_{elev} \end{bmatrix} \quad (3.3)$$

In Eq. (3.3), the control input δ_{elev} refers to the symmetric deflection of the VISTA's horizontal stabilator.

The corresponding state-space output equation $y = \mathbf{Cx} + \mathbf{Du}$ for this short period longitudinal system is,

$$y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha \\ q \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \begin{bmatrix} \delta_{elev} \end{bmatrix}. \quad (3.4)$$

Finally to establish the convention that positive elevator deflection results in positive changes in q and α , the sign of the SRF generated \mathbf{B} matrix of Eq. (3.3) is negated.

Since the SRF linearization scheme completely decouples the longitudinal and lateral/direction channels (Eq. (3.1)), the δ_{flap} is eliminated as a control input, and the short period approximation is applied, the resulting longitudinal system appears to be a 2nd-order single-input single-output (SISO) system. However as Chap. IV explains, control effector failure induces an additional input into the system, yielding a multiple-input single-output (MISO) system.

3.5 Lateral/Directional Aircraft Model

Unlike the longitudinal channel where the short period approximation is made, the full lateral state-space model including the roll, dutch roll, and spiral modes is used in the lateral channel design. The lateral state-space model extracted from Eq. (3.1) is listed in Eq. (3.5).

$$\begin{bmatrix} \dot{\phi} \\ \dot{\beta} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & \phi_r \\ Y_\phi & Y_\beta & Y_p & Y_r \\ 0 & L_\beta & L_p & L_r \\ 0 & N_\beta & N_p & L_r \end{bmatrix} \begin{bmatrix} \phi \\ \beta \\ p \\ r \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ Y_{\delta_{df tail}} & Y_{\delta_{ail}} & Y_{\delta_{rud}} \\ L_{\delta_{df tail}} & L_{\delta_{ail}} & L_{\delta_{rud}} \\ N_{\delta_{df tail}} & N_{\delta_{ail}} & N_{\delta_{rud}} \end{bmatrix} \begin{bmatrix} \delta_{df tail} \\ \delta_{ail} \\ \delta_{rud} \end{bmatrix} \quad (3.5)$$

In Eq. (3.5) the three control inputs $\delta_{df tail}$, δ_{ail} , and δ_{rud} correspond to differential deflection of the horizontal stabilator, aileron deflection, and rudder deflection, respectively.

The corresponding state-space output equation $y = \mathbf{Cx} + \mathbf{Du}$ for the lateral system is,

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \phi \\ \beta \\ p \\ r \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_{df tail} \\ \delta_{ail} \\ \delta_{rud} \end{bmatrix} \quad (3.6)$$

Similar to the action taken in the longitudinal channel, the sign of the SRF generated \mathbf{B} matrix of Eq. (3.5) is negated. This action establishes the convention that positive aileron and differential tail deflection results in a positive change in p and the convention that a positive rudder deflection results in a positive change in r and a negative change in β .

Ultimately the lateral plant model represents a 3 X 2 aircraft system with an additional disturbance input added to model coupling of the lateral/directional and longitudinal aircraft channels as explained in Chap. IV.

3.6 Transfer Function Generation

The LTI aircraft models developed in previous sections must be manipulated into the transfer function format for input into the QFT CAD. The development of these transfer function matrices follows from the state-space representation identified in Eqs. (3.7) and (3.8), where the the disturbance Γ matrix is discussed in Chap. III.

$$\dot{\mathbf{x}}(t) = \mathbf{Ax}(t) + \mathbf{Bu}(t) + \Gamma d(t) \quad (3.7)$$

$$\mathbf{y}(t) = \mathbf{Cx}(t) \quad (3.8)$$

Transforming Eqs. (3.7) and (3.8) into the Laplace domain and manipulating the state space representation into transfer function format:

$$\mathbf{y}(s) = \mathbf{P}(s)\mathbf{u}(s) + \mathbf{P}_D(s)\mathbf{d}(s) \quad (3.9)$$

where:

$$\mathbf{P}(s) = \mathbf{C}[s\mathbf{I} - \mathbf{A}]^{-1}\mathbf{B} \quad (3.10)$$

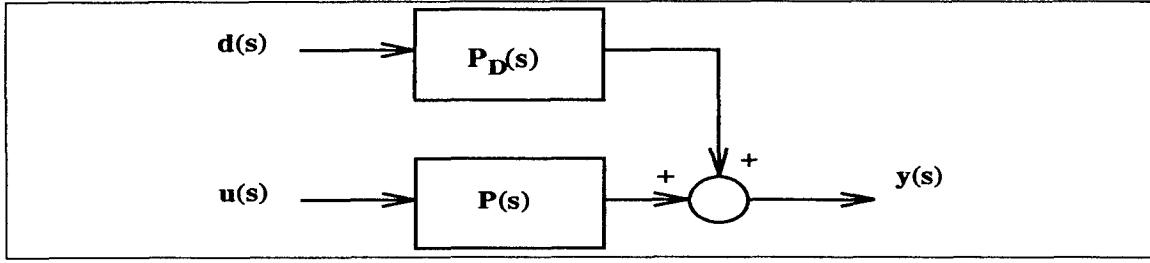


Figure 3.2 Block Diagram of Plant and External Disturbance Input

$$P_D(s) = C[sI - A]^{-1} \Gamma \quad (3.11)$$

Equation 3.9 is symbolically represented in Fig. 3.2.

Substituting Eqs. (3.10) and (3.11) into Eq. (3.9):

$$y(s) = C[sI - A]^{-1} Bu + C[sI - A]^{-1} \Gamma d(s) \quad (3.12)$$

Finally, Eq. (3.9) is automated via the 'ss2tf' *Matlab* function and the appropriate transfer function matrices (P and P_D) are generated.

3.7 Actuator Model

The fourth-order actuator model used in Reynold's thesis is also chosen for this design and has the transfer function given in Eq. (3.13).

$$\frac{\delta_{control}(s)}{\delta_{control(cmd)}(s)} = \frac{(20.2)(71.4)^2(144.8)}{(s + 20.2)(s + 144.8)[s^2 + 2(0.736)(71.4)s + (71.4)^2]} \quad (3.13)$$

The "control" subscript in Eq. (3.13) refers to any of the control surfaces of the aircraft. As discussed in Reynold's thesis, a fourth-order model is chosen to replace the simpler first-order model because the higher-order model adds approximately 50 degrees of phase lag to the system at 30 rps and even more at higher frequencies. This additional phase lag has a significant impact on the designer's ability to stabilize the system, and, as Reynolds suggests, "should always be used in robust control design"[16].

IV. Control Surface Failure Modeling

Aerodynamic control effector failures have two significant effects on an airframe. The first, and most direct, effect is the attenuation of the forces and moments the control surfaces can generate. The second, and less obvious effect of aerodynamic control surface damage, is the alteration of an aircraft's dynamics as represented by its stability derivatives. In 1993 Captain Mark Keating derived the equations to model the effect of control surface failures on an aircraft's control and stability derivatives. Though these equations were developed for the Lambda Unmanned Research Vehicle (URV), they can be adapted to accommodate any airframe. This chapter overviews Keating's pioneering work and develops the modifications needed to adapt his failure model to the VISTA F-16.

4.1 Longitudinal Stability and Control Derivatives

The effect of control surface failure can be determined by analyzing the three non-dimensionalized longitudinal equations of motion found, e.g., in Blakelock [2].

$$\left(\frac{mU}{S\bar{q}}\dot{u} - C_{x_u}u\right) + \left(-\frac{c}{2U}C_{x_\alpha}\dot{\alpha} - C_{x_\alpha}\alpha\right) + \left(-\frac{c}{2U}C_{x_q}\dot{\theta} - C_w(\cos\Theta)\theta\right) = C_{x_{\delta_e}}\delta_e \quad (4.1)$$

$$-C_{z_u}u + \left(\frac{mU}{S\bar{q}} - \frac{c}{2U}C_{z_\alpha}\right)\dot{\alpha} - C_{z_\alpha}\alpha + \left(-\frac{mU}{S\bar{q}} - \frac{c}{2U}C_{z_q}\right)\dot{\theta} - C_w(\sin\Theta)\theta = C_{z_{\delta_e}}\delta_e \quad (4.2)$$

$$-C_{m_u}u + \left(\frac{c}{2U}C_{m_\alpha}\dot{\alpha} - C_{m_\alpha}\alpha\right) + \left(\frac{I_y}{S\bar{q}c}\ddot{\theta} - \frac{c}{2U}C_{m_q}\dot{\theta}\right) = C_{m_{\delta_e}}\delta_e \quad (4.3)$$

Keating made the following assumptions:

1. Fuselage effects are negligible.
2. Control surface failure has a negligible impact on the stability derivatives in the longitudinal Eq. (4.1), consequently this equation can be removed from consideration.
3. The (battle) damage does not change the aircraft's mass significantly, thus C_w can be neglected.

Eliminating Eq. (4.1) leaves only the Z equation (Eq. (4.2)) and the M equation (Eq. (4.3)) to be analyzed, which are utilized in the current research since only the short period dynamics are of interest.

4.1.1 M Equation Analysis. Some further simplifications to Eq. (4.3) can be made by neglecting C_{m_u} and C_{m_α} . C_{m_u} is due primarily to the lift generated on the wing, thus elevator damage has little effect on this stability derivative, and C_{m_α} accounts for downwash effects which are assumed to be negligible (see Chap. I). Eliminating the aforementioned stability derivatives leaves only the changes in C_{m_α} , C_{m_q} and $C_{m_{\delta_e}}$ to be considered.

First, the C_{m_α} stability derivative is discussed. The purpose of this derivation is to isolate the moment generated by the wing-body structure from the moment generated by the tail section. By isolating moments the effects of tail surface removal can be determined explicitly. From Roskam Eq.(4.21)[17] the total aerodynamic moment M_A is expressed as

$$M_A = \bar{q}S_w \bar{c}C_{M_{total}} \quad (4.4)$$

where \bar{q} is the dynamic pressure, S_w is the aerodynamic area of the wing, \bar{c} is the mean aerodynamic chord (MAC), and $C_{M_{total}}$ is the total aerodynamic moment defined in Eq. (4.7).

$$C_{M_{total}} = C_{M_{total_1}} + C_{M_{total_2}} \quad (4.5)$$

where

$$C_{M_{total_1}} = (C_{L_{o_{wb}}} + C_{L_{\alpha_{wb}}}\alpha)(\bar{X}_{CG} - \bar{X}_{AC_{wb}}) \quad (4.6)$$

$$C_{M_{total_2}} = C_{m_{AC_{wb}}} - C_{L_{\alpha_t}}\eta_t \frac{S_t}{S_w}(\bar{X}_{AC_t} - \bar{X}_{CG})[\alpha + (\epsilon_o + \frac{d\epsilon}{dt}\alpha) + i_t] \quad (4.7)$$

The substitutions in Eqs. (4.8) through (4.13) are made to further simplify Eqs. (4.6) and (4.7).

$$a_t \equiv C_{L_{\alpha_t}} \quad (4.8)$$

$$a_w \equiv C_{L_{\alpha_{wb}}} \quad (4.9)$$

$$l_t \equiv (\bar{X}_{AC_t} - \bar{X}_{CG}) \quad (4.10)$$

$$\Delta X_{CG} \equiv (\bar{X}_{CG} - \bar{X}_{AC_{wb}}) \quad (4.11)$$

$$\eta_t \equiv \frac{\bar{q}_t}{\bar{q}} \quad (4.12)$$

$$k \equiv \frac{d\epsilon}{dt} \quad (4.13)$$

Where a_t and a_w represent the slopes of the tail and wing lift vs. α curve respectively, ΔX_{CG} is the distance between the aircraft center of gravity and the aerodynamic center of the wing-body(wb), l_t is the effective distance between the aerodynamic center of the horizontal stabilator and the aircraft's center of gravity, η_t is the dynamic pressure attenuation ratio at the tail, and k is the downwash angle gradient. For the VISTA F-16 a_t and a_w are assumed to be nearly identical and are determined along with ΔX_{CG} from the SRF data for each plant case. The effective tail arm length l_t is extrapolated from the VISTA F-16 schematic as the distance between the tail and the nominal center of gravity at FS320.654, approximately 15.86 feet. A dynamic pressure ratio η_t of 0.90, and a downwash gradient k of 0.33 are used in this design. The interested reader is directed to the literature [17] for a more detailed explanation of these last two constants.

Making the appropriate substitutions into Eq. (4.5):

$$C_{M_{total}} = (C_{L_{wb}} + a_w \alpha) \Delta X_{CG} + C_{m_{AC_{wb}}} - a_t \eta_t \frac{S_t}{S_w} l_t (1 - k) \alpha \quad (4.14)$$

Eq. (4.14) is then substituted into Eq. (4.4) and rewritten as:

$$M_{total} = \bar{q} S_w \bar{c} \left[(C_{L_{wb}} + a_w \alpha) \Delta X_{CG} + C_{m_{AC_{wb}}} - a_t \eta_t \frac{S_t}{S_w} l_t (1 - k) \alpha \right] \quad (4.15)$$

The total aerodynamic moment in Eq. (4.15) can be subdivided into a moment due to the wing and a moment due to the tail as shown in Eq. (4.16).

$$M_{total} = M_{wing} + M_{tail} \quad (4.16)$$

By regrouping terms in Eq. (4.15) corresponding to Eq. (4.16) the following two equations emerge.

$$M_{wing} = \bar{q} S_w \bar{c} \left[(C_{L_{wb}} + a_w \alpha) \Delta X_{CG} + C_{m_{AC_{wb}}} \right] \quad (4.17)$$

$$M_{tail} = -\bar{q} \bar{c} a_t \eta_t S_t l_t (1 - k) \alpha \quad (4.18)$$

Assuming that the lift coefficient at $\alpha = 0$ ($C_{L_{o_w}}$) and the moment coefficient due to the difference between the wing aerodynamic center and the center of gravity ($C_{m_{AC_w}}$) terms do not change with removal of tail surface area, Keating's Eqs. (3.4) and (3.5), respectively, are:

$$M_{wing} = \bar{q}cS_wa_w\Delta X_{CG}\alpha \quad (4.19)$$

$$M_{tail} = -\bar{q}c\eta_t S_t a_t l_t (1 - k)\alpha \quad (4.20)$$

Unlike the URV, the ΔX_{CG} for the VISTA is negative since the aircraft is statically unstable. Therefore both M_{wing} and M_{tail} are negative and hence develop a negative M_{total} shown in Eq. (4.21).

$$-M_{total} = \bar{q}c[S_wa_w\Delta X_{CG} + \eta_t S_t a_w l_t (1 - k)]\alpha \quad (4.21)$$

Now M_{total} is defined as $-(M_{\alpha UF})\alpha$ or in other words the dimensional stability derivative for the undamaged aircraft (UF) multiplied by α .

$$M_{\alpha UF} = \bar{q}c[S_wa_w\Delta X_{CG} + \eta_t S_t a_w l_t (1 - k)] \quad (4.22)$$

The VISTA F-16 does not have trailing edge elevators as on the URV, therefore the damaged area of the horizontal stabilator corresponds to the damaged area of the elevator. This difference in the design of the elevator between Lambda and VISTA simplifies some of Keating's equations in application to the VISTA F-16 failure problem; for example, Keating defined an additional damage variable ζ_e found in Eq. (4.23)

$$\zeta_e = \frac{(\zeta_e - 1)S_e + S_t}{S_t} \quad (4.23)$$

to isolate the damage to the control effector rather than effecting the entire horizontal stabilator. However in the VISTA F-16(see Table 3.1), the aerodynamic area of the elevator (S_e) and the aerodynamic area of the tail (S_t) are identical hence $\zeta_e = \zeta_e$. This ζ_e replacement is made throughout the longitudinal channel failure analysis to modify Keating's equations to the VISTA F-16.

With a damaged elevator, the dimensional stability derivative ($M_{\alpha F}$) becomes:

$$M_{\alpha F} = \bar{q}\bar{c}[S_w a_w \Delta X_{CG} + \zeta_e \eta_t S_t a_w l_t (1 - k)] \quad (4.24)$$

where ζ_e is added to Eq. (4.22) representing the proportion of tail area remaining after damage. If $\zeta_e = 1$ then the aircraft remains undamaged and if $\zeta_e = .75$ then the aircraft has experienced a 25% reduction in horizontal stabilator area.

The effect on C_{m_α} can be expressed in terms of the change in dimensional stability derivatives (ΔM_α) where

$$\Delta M_\alpha = M_{\alpha UF} - M_{\alpha F} \quad (4.25)$$

Substituting Eqs. (4.22) and (4.24) into Eq. (4.25) yields

$$\Delta M_\alpha = \bar{q}\bar{c}[(1 - \zeta_e)\eta S_t a_t l_t (1 - k)] \quad (4.26)$$

To non-dimensionalize this change, Eq. (4.26) is divided by Eq. (4.24).

$$\frac{\Delta M_\alpha}{M_\alpha} = \frac{(1 - \zeta_e)\eta S_t a_t l_t (1 - k)}{[S_w a_w \Delta X_{CG} + \zeta_e \eta_t S_t a_w l_t (1 - k)]} \quad (4.27)$$

This ratio represents the fraction of $C_{m_{\alpha UF}}$ which has been lost due to damage. Therefore, the first damaged dimensionless stability derivative is

$$C_{m_{\alpha F}} = C_{m_{\alpha UF}} \left[1 - \left(\frac{\Delta M_\alpha}{M_\alpha} \right) \right] \quad (4.28)$$

Figure 4.1 shows the relationship between the damage level ($1 - \zeta_e$) and the change in the nondimensional stability derivative $C_{m_{\alpha F}}$. From this figure it can be seen that as ζ_e decreases, or, as the damage level increases, $C_{m_{\alpha F}}$ decreases. This is the anticipated result, because it indicates that the system becomes increasingly unstable without the stabilizing effect of the healthy horizontal stabilator.

The remaining derivatives, C_{m_g} and $C_{m_{\delta_e}}$, show a simple proportional relationship between the effective area of the tail and the respective value of the stability derivative.

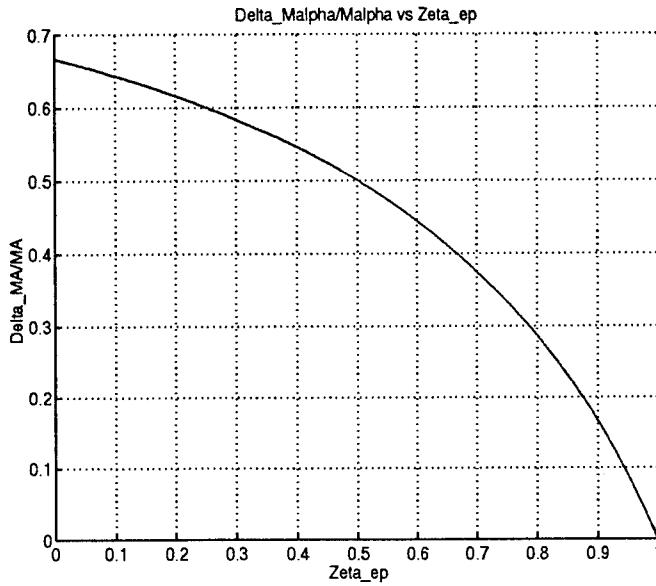


Figure 4.1 $\frac{\Delta M_\alpha}{M_\alpha}$ vs. ζ_e

These relationships are shown in Eqs. (4.29) and (4.30).

$$C_{m_{qF}} = \zeta_e C_{m_{qUF}} \quad (4.29)$$

$$C_{m_{\delta_e F}} = \zeta_e C_{m_{\delta_e UF}} \quad (4.30)$$

4.1.2 Z Equation Analysis. Eq. (4.2) (repeated below) describes the forces in the z-axis direction.

$$-C_{z_u}u + \left(\frac{mU}{S\bar{q}} - \frac{c}{2U}C_{z\dot{\alpha}}\right)\dot{\alpha} - C_{z\alpha}\alpha + \left(-\frac{mU}{S\bar{q}} - \frac{c}{2U}C_{zq}\right)\dot{\theta} - C_w(\sin\Theta)\theta = C_{z\delta_e}\delta_e \quad (4.31)$$

Following a similar line of reasoning employed for the M equation analysis, the u and $\dot{\alpha}$ stability derivatives as well as C_w are neglected. The analysis for $C_{z\alpha}$ is nearly identical to C_{m_α} , with the goal of the ensuing derivation to once again isolate the effects of the wing-body and tail airframe components on the aircraft's dynamics. In this situation, however, the forces in the z direction are examined and not the moments they generate.

Once again, isolating the effects of the wing and body Eq. (4.32) emerges.

$$Z_{total} = Z_{wing} + Z_{tail} \quad (4.32)$$

where Eqs. (4.33) and (4.34) are developed by removing the moment arm from Eqs. (4.19) and (4.20) and conforming to the convention that the lift acts in the negative z direction.

$$Z_{wing} = -\bar{q}S_w a_w \alpha \quad (4.33)$$

$$Z_{tail} = -\bar{q}\eta S_t a_t (1 - k) \alpha \quad (4.34)$$

Substituting Eqs. (4.33) and (4.34) into (4.32) yields:

$$Z_{total} = -\bar{q}\alpha[S_w a_w + \eta S_t a_t (1 - k)] \quad (4.35)$$

Now Z_{total} is defined as $Z_{\alpha UF}\alpha$ or in other words the dimensional stability derivative for the undamaged aircraft(*UF*) multiplied by α .

$$Z_{\alpha UF} = -\bar{q}[S_w a_w + \eta S_t a_t (1 - k)] \quad (4.36)$$

Following the damage level convention established for the *M* equation, Eq. (4.37) is developed by removing a portion of the tail surface area S_t with the addition of the scaling term ζ_e and the (*F*) notation.

$$Z_{\alpha F} = -\bar{q}[S_w a_w + \zeta_e \eta S_t a_t (1 - k)] \quad (4.37)$$

The damage level effects on Z_α can then be quantified by taking the difference between the failed and unfailed Z_α terms. The results are found in Eq. (4.38).

$$\Delta Z_\alpha = Z_{\alpha UF} - Z_{\alpha F} \quad (4.38)$$

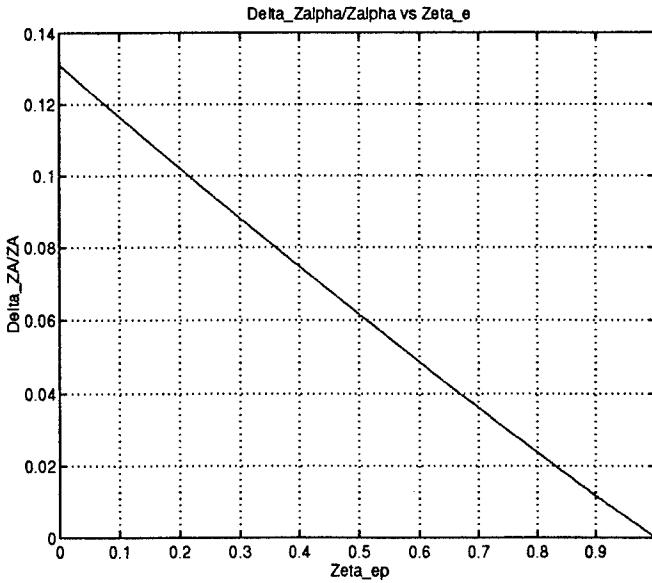


Figure 4.2 $\frac{\Delta Z_\alpha}{Z_\alpha}$ vs ζ_e

Substituting Eqs. (4.35) and (4.37) into Eq. (4.38) yields:

$$\Delta Z_\alpha = -\bar{q}(1 - \zeta_e)\eta S_t a_t(1 - k) \quad (4.39)$$

In order to nondimensionalize the change in Z_α , Eq. (4.39) is divided by Eq. (4.35) producing:

$$\frac{\Delta Z_\alpha}{Z_\alpha} = \frac{(1 - \zeta_e)\eta S_t a_t(1 - k)}{S_w a_w + \eta S_t a_t(1 - k)} \quad (4.40)$$

Finally a general equation is derived that can transform a healthy dimensional or nondimensional stability derivative into a stability derivative reflecting the effects of control surface effector removal.

$$C_{z_{\alpha F}} = C_{z_{\alpha UF}} \left[1 - \frac{\Delta Z_\alpha}{Z_\alpha} \right] \quad (4.41)$$

Figure 4.2 shows the effect of increased damage level on the change in Z_α .

Referring back to Eq. (4.2) the only coefficients that are left for discussion are C_{z_q} and $C_{z_{\delta_e}}$. Since the lift generated during a pitching motion (C_{z_q}), and the lift generated by deflection of the horizontal stabilator are both directly related to the tail surface area

the failure analysis for the Z equation is completed with Eqs. (4.42) and (4.43).

$$C_{z_{qF}} = \zeta_e C_{z_{qUF}} \quad (4.42)$$

$$C_{z_{\delta_e F}} = \zeta_e C_{z_{\delta_e UF}} \quad (4.43)$$

4.2 Lateral Stability and Control Derivatives

In addition to the control effectors found on the Lambda URV, the VISTA also includes the use of the differential tail to be used in roll control. This additional control effector is similar to the aileron. Hence in the failure analysis that follows the differential tail is treated as an additional aileron input into the system.

Maintaining consistency with the longitudinal failure analysis, the respective damage levels ζ_a , ζ_r , and ζ_{dt} represent the percentage of aileron, rudder, and differential tail surface area removed after control effector failure.

Unlike the longitudinal channel, no approximations are employed to reduce the dynamics of interest and consequently the failure analysis of the full lateral aircraft dynamics is developed. The equations of motion for the lateral channel are found in Blakelock [2] and are listed below.

$$-\frac{b}{2U}C_{y_p}\dot{\phi} - C_{y_{\phi}\phi} + \left(\frac{mU}{S\bar{q}} - \frac{b}{2U}C_{y_r}\right)\dot{\psi} - C_{y_{\psi}}\psi + \frac{mU}{S\bar{q}}\dot{\beta} - C_{y\beta}\beta = C_{y_{\delta_a}}\delta_a + C_{y_{\delta_r}}\delta_r + C_{y_{\delta_{dt}}}\delta_{dt} \quad (4.44)$$

$$\frac{I_x}{S\bar{q}b}\ddot{\phi} - \frac{b}{2U}C_{l_p}\dot{\phi} - \frac{J_{xz}}{S\bar{q}b}\ddot{\psi} - \frac{b}{2U}C_{l_r}\dot{\psi} - C_{l\beta} = C_{l_{\delta_a}}\delta_a + C_{l_{\delta_r}}\delta_r + C_{l_{\delta_{dt}}}\delta_{dt} \quad (4.45)$$

$$-\frac{J_{xz}}{S\bar{q}b}\ddot{\phi} - \frac{b}{2U}C_{n_p}\dot{\phi} + \frac{I_z}{S\bar{q}b}\ddot{\psi} - \frac{b}{2U}C_{n_r}\dot{\psi} - C_{n\beta}\beta = C_{n_{\delta_a}}\delta_a + C_{n_{\delta_r}}\delta_r + C_{n_{\delta_{dt}}}\delta_{dt} \quad (4.46)$$

4.2.1 Y Equation. The Y equation is repeated below:

$$-\frac{b}{2U}C_{y_p}\dot{\phi} - C_{y_{\phi}\phi} + \left(\frac{mU}{S\bar{q}} - \frac{b}{2U}C_{y_r}\right)\dot{\psi} - C_{y_{\psi}}\psi + \frac{mU}{S\bar{q}}\dot{\beta} - C_{y\beta}\beta = C_{y_{\delta_a}}\delta_a + C_{y_{\delta_r}}\delta_r + C_{y_{\delta_{dt}}}\delta_{dt} \quad (4.47)$$

C_{y_p} , C_{y_r} , and $C_{y\beta}$ represent the magnitude of the side force created by each of the lateral states of the aircraft, and each of these stability derivatives is directly proportional

to aerodynamic control effector area. Consequently, the vertical stabilator is the only control effector that develops a y directional force, hence Eqs. (4.48), (4.49), and (4.50) are established.

$$C_{y_{pF}} = \zeta_r C_{y_{pUF}} \quad (4.48)$$

$$C_{y_{rF}} = \zeta_r C_{y_{pUF}} \quad (4.49)$$

$$C_{y_{\beta F}} = \zeta_r C_{y_{pUF}} \quad (4.50)$$

Where the effective area of the vertical stabilator or ζ_r is determined by removing the damaged rudder area $(\zeta_r - 1)S_r$ from the vertical stabilator area S_f as shown in Eq. (4.51).

$$\zeta_r = \frac{(\zeta_r - 1)S_r + S_f}{S_f} \quad (4.51)$$

Each of the control derivatives are directly proportional to the effective area of their respective control effector area. Eqs. (4.52) through (4.54) reflect this proportional relationship.

$$C_{y_{\delta_r F}} = \zeta_r C_{y_{\delta_r UF}} \quad (4.52)$$

$$C_{y_{\delta_a F}} = \zeta_a C_{y_{\delta_a UF}} \quad (4.53)$$

$$C_{y_{\delta_d F}} = \zeta_d C_{y_{\delta_d UF}} \quad (4.54)$$

Since the aileron deflection on the VISTA F-16 creates a negligible force in the y direction, $C_{y_{\delta_a UF}} = 0$.

4.2.2 L Equation. The L equation is repeated below:

$$\frac{I_x}{S\bar{q}b}\ddot{\phi} - \frac{b}{2U}C_{l_p}\dot{\phi} - \frac{J_{xz}}{S\bar{q}b}\ddot{\psi} - \frac{b}{2U}C_{l_r}\dot{\psi} - C_{l_\beta} = C_{l_{\delta_a}}\delta_a + C_{l_{\delta_r}}\delta_r + C_{l_{\delta_d}}\delta_d \quad (4.55)$$

The C_{l_p} derivative represents the damping of the aircraft's rolling moment. Keating reasoned that only the wings and horizontal tail surface area significantly contributes to the magnitude of C_{l_p} . Therefore, Keating removed the vertical stabilator from consideration in the failure analysis. However, Roskam's Eq. (4.159) repeated below as Eq. (4.56) shows

that the vertical stabilator does contribute to C_{l_p} .

$$C_{l_p} = C_{l_{wb}} + C_{l_{pH}} + C_{l_{pV}} \quad (4.56)$$

where wb , H , and V represent the wingbody, horizontal and vertical tail aircraft components respectively.

Based on Eq. (4.56) and VISTA's substantially greater vertical stabilator area than the Lambda URV, the inclusion of the vertical stabilator in the failure analysis is warranted. The end result of this derivation is Eq. (4.57) which establishes the relationship between the failed C_{l_pF} derivative and the effective area of the wings, and both stabilators remaining after control effector failure.

$$C_{l_pF} = \zeta_{ar} Cl_{pUF} \quad (4.57)$$

where

$$\zeta_{ar} = \frac{(\delta_{dt} - 1)S_t + (\delta_a - 1)S_a + (\delta_r - 1)S_r + S_w + S_f + St}{S_w + S_f + St} \quad (4.58)$$

Only the vertical stabilator provides r and β damping thus C_{l_r} and C_{l_β} are both proportional to the effective area of the vertical stabilator.

$$C_{l_{rF}} = \zeta_r Cl_{rUF} \quad (4.59)$$

$$C_{l_{\beta F}} = \zeta_r Cl_{\beta UF} \quad (4.60)$$

The control derivatives are once again proportional to the control surface area and Eqs. (4.61) through (4.63) reflect this relationship.

$$C_{l_{\delta_a F}} = \zeta_a Cl_{\delta_a UF} \quad (4.61)$$

$$C_{l_{\delta_r F}} = \zeta_r Cl_{\delta_r UF} \quad (4.62)$$

$$C_{l_{\delta_{dt} F}} = \zeta_{dt} Cl_{\delta_{dt} UF} \quad (4.63)$$

4.2.3 N Equation. The N equation is repeated below:

$$-\frac{J_{xz}}{S\bar{q}b}\ddot{\phi} - \frac{b}{2U}C_{n_p}\dot{\phi} + \frac{I_z}{S\bar{q}b}\ddot{\psi} - \frac{b}{2U}C_{n_r}\dot{\psi} - C_{n\beta}\beta = C_{n_{\delta_a}}\delta_a + C_{n_{\delta_r}}\delta_r + C_{n_{\delta_{dt}}}\delta_{dt} \quad (4.64)$$

All of the N stability derivatives are directly proportional to the effective area of the vertical stabilator and these relationships are quantified in the following equations:

$$C_{n_{pF}} = \zeta_r C_{n_{pUF}} \quad (4.65)$$

$$C_{n_{rF}} = \zeta_r C_{n_{rUF}} \quad (4.66)$$

$$C_{n_{\beta F}} = \zeta_r C_{n_{\beta UF}} \quad (4.67)$$

The control derivatives are also directly proportional to their respective aerodynamic surfaces as found in the following equations:

$$C_{n_{\delta_a F}} = \zeta_a C_{n_{\delta_a UF}} \quad (4.68)$$

$$C_{n_{\delta_r F}} = \zeta_r C_{n_{\delta_r UF}} \quad (4.69)$$

$$C_{n_{\delta_{dt} F}} = \zeta_{dt} C_{n_{\delta_{dt} UF}} \quad (4.70)$$

4.3 Disturbance Modeling

Keating introduced an external disturbance into both the longitudinal and lateral channels to model the inherent cross-coupling created by asymmetric control effector failure. In the longitudinal channel this external disturbance represents the effect of losing a portion of the horizontal stabilator on the trim of the aircraft, and in the lateral channel this external disturbance represents the additional rolling moment and sideslip angle introduced by a damaged horizontal stabilator. Both of these VISTA models referred to in Keating's work as Γ_{lat} and Γ_{long} , are identical to the Lambda research vehicle and are completely explained in Keating's Thesis. The general models are given in Eqs. (4.71) through (4.74).

4.3.1 Longitudinal Model.

$$\dot{\mathbf{x}}_d = \mathbf{A}\mathbf{x}_d + \boldsymbol{\Gamma}_{\text{long}}\delta_{\text{trim}} \quad (4.71)$$

$$\begin{bmatrix} \dot{u}_d \\ \dot{\alpha}_d \\ \dot{q}_d \\ \dot{\theta}_d \end{bmatrix} = \mathbf{A} \begin{bmatrix} u_d \\ \alpha_d \\ q_d \\ \theta_d \end{bmatrix} + \frac{1 - \zeta_e}{\zeta_e} \begin{bmatrix} 0 \\ \frac{Z_{\delta_e}}{U - Z_{\dot{\alpha}}} \\ M_{\delta_e} + \frac{M_{\dot{\alpha}}Z_{\delta_e}}{U - Z_{\dot{\alpha}}} \\ 0 \end{bmatrix} \delta_{\text{trim}} \quad (4.72)$$

4.3.2 Lateral Model.

$$\dot{\mathbf{x}}_d = \mathbf{A}\mathbf{x}_d + \boldsymbol{\Gamma}_{\text{lat}}\delta_e \quad (4.73)$$

$$\begin{bmatrix} \dot{\beta}_d \\ \dot{p}_d \\ \dot{\phi}_d \\ \dot{r}_d \end{bmatrix} = \mathbf{A} \begin{bmatrix} \beta_d \\ p_d \\ \phi_d \\ r_d \end{bmatrix} + \frac{1 - \zeta_e}{\zeta_e} \begin{bmatrix} 0 \\ \frac{L_{\delta_a U F}}{6\Lambda} \\ 0 \\ \frac{\kappa_\nu L_{\delta_a U F}}{6\Lambda} \end{bmatrix} \delta_{\text{trim}} \quad (4.74)$$

where $\delta_{\text{trim}} \approx 5$ degrees, $\Lambda = 1 - \frac{J_{zz}^2}{I_x I_z}$, and $\kappa_\nu = J_{xz}/I_z$

4.4 Failure Model Generation

From the failure analysis, the relationships are established to model failures as changes in the dimensional or nondimensional stability and control derivatives. These derivatives are acquired from Phillips' 1994 design.[15] The plants are edited for input into *Matlab*, and loaded into a *Matlab* script file (Appendix A) where the failure analysis is performed according to the equations developed previously. The failed plants in the form of **A** and **B** matrices are then loaded into another script file that forms the appropriate transfer functions including the disturbance functions, and are then formatted for input into QFTCAD. This procedure is used in both longitudinal and lateral/directional designs to generate the failure models for this design, and is outlined in Fig. 4.3.

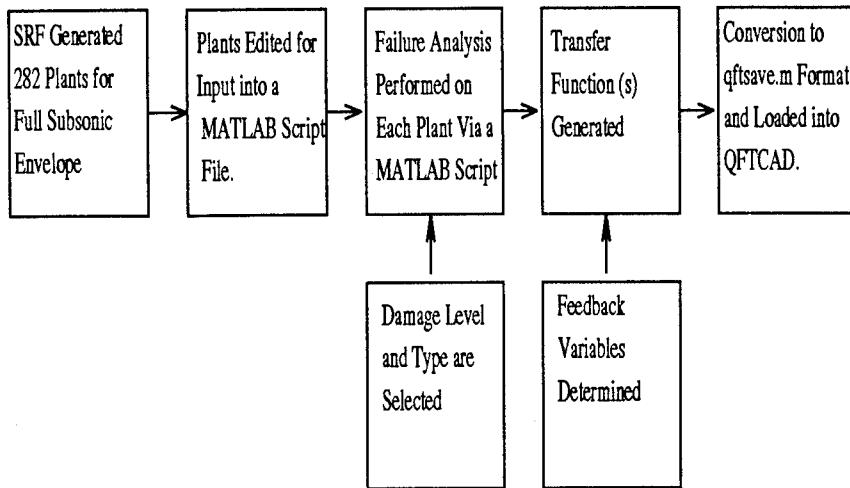


Figure 4.3 Failure Modeling Automation Flow Diagram

4.5 Failure Modeling Summary

In this chapter, Keating's failure modeling scheme is examined and the necessary changes are made to accommodate the VISTA F-16. The most prominent adaptations made to Keating's equations involves the obvious differences between the URV and VISTA airframes. Some of these differences are: the URV has two small rudders working in tandem versus the VISTA which has a single, large rudder, the URV has trailing edge elevators while the VISTA has a stabilator, and the URV uses only ailerons while the VISTA incorporates both the ailerons and differential tail for roll control. Given these adaptations Keating's analysis is extended to the VISTA F-16, and the focus is shifted towards developing the external disturbance failure models. Ultimately, the actual failure model generation is discussed, and an overview of the entire sequence of events in the failure modeling process is given in Fig. 4.3.

V. Longitudinal FCS Design

The purpose of this chapter is to examine the entire longitudinal design process from the generation of the feedback variables to compensator design and specification validation.

5.1 Longitudinal Design

5.1.1 Longitudinal QFT Structure. The first step in any QFT design is to define the feedback structure. To simulate the failure effects discussed in Chap. IV, an external disturbance plant in Fig. 5.1 is added to the general MISO QFT structure found in Fig. 2.1. Furthermore, in this research the longitudinal channel structure is of particular interest because, unlike traditional methods, an innovation is employed as the feedback variable. This variable C^* is actually a blending of the pitch rate q and the normal acceleration at the pilot's station N_z . This blending was the result of Phillips' research. As an experienced F-16 pilot, he reasoned that at low dynamic pressure \bar{q} the pilot is focused on tracking the pitch rate since the g loading is unavailable. However when the energy state of the aircraft is increased, the pilot shifts his attention towards tracking normal acceleration. This shift in focus is simulated through the use of the C^* variable, which represents a weighted combination of the q and N_z aircraft states (See Eqs. (5.1) and (5.2)).

$$C^* = K_1 q + K_2 N_z \quad (5.1)$$

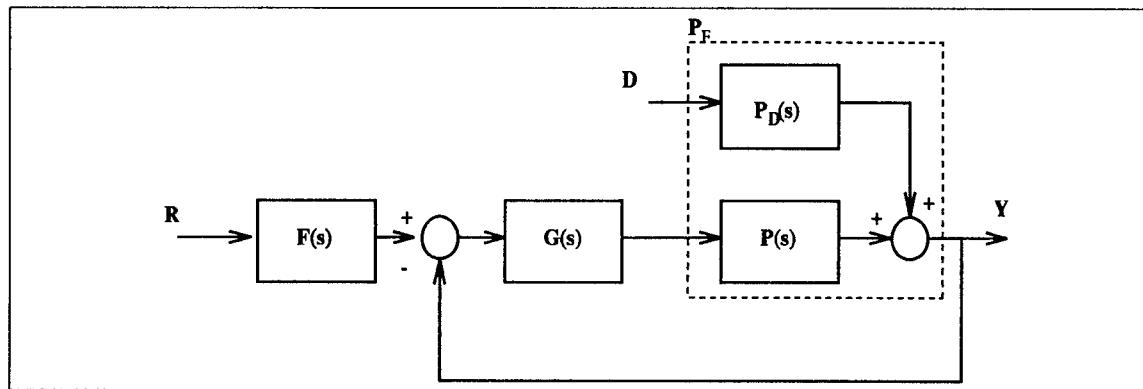


Figure 5.1 Longitudinal QFT Feedback Structure

$$N_z = \left(\frac{\pi}{5796}\right)[U(\dot{\alpha} - q) - l_x \dot{q}] \quad (5.2)$$

Note that l_x is the distance from the pilot station to nominal aircraft center of gravity, approximately 13.95 feet, and U is the trim velocity in the x body axis direction. Further explanation of the N_z equation derivation is provided in Reynold's thesis [16].

The C^* weighting is \bar{q} dependent and the gradient adopted in this research is shown in Fig. 5.2. The two lines on this gradient represent the relative gains K_1 and K_2 in Eq. (5.1). At low \bar{q} , q is the dominant feedback variable, and at high \bar{q} , N_z dominates. This gradient is designed such that the crossing point, represented by the equal weighting of the two feedback variables, occurs at approximately 200 lbs/ ft^2 , and the gains, K_1 and K_2 settle to 0.8 and 0.2 above 600 lbs/ ft^2 . It is also worth mentioning that the asymptotic gradient in Fig. 5.2 is not the same C^* gradient found in Fig. 4.3 of Phillips' thesis. Phillips spent a considerable portion of his research refining the C^* variable, and in that time, attempted various blending schemes. From this work, he determined that the asymptotic scheme most accurately represented the pilot's tracking tendencies, and hence included it in the formulation of C^* . As a simple oversight, however, the linear gradient was printed in his thesis instead of the asymptotic gradient. As a consequence of this oversight, the linear weighting in Fig. 4.3 is attempted in the current design, and an interesting finding emerges in the process. The gradient with the linear weighting generates greater parametric plant uncertainty within the pilots bandwidth than the asymptotic weighting. This increase in uncertainty within the pilots bandwidth suggests that the incorporation of the physical world actually improves the design, and ultimately motivates the application of the asymptotic scheme in this research.

Due to the static instability of the VISTA F-16 in the subsonic envelope, it is traditional to incorporate an inner loop for stability purposes. However, Phillips found for the VISTA that an inner loop needlessly complicated the feedback structure while shifting the plant uncertainty from the pilot's bandwidth towards the higher frequency ranges. This shift limits the pilot's ability to control the aircraft and is deemed unacceptable. Hence, an inner loop design is not included in this research.

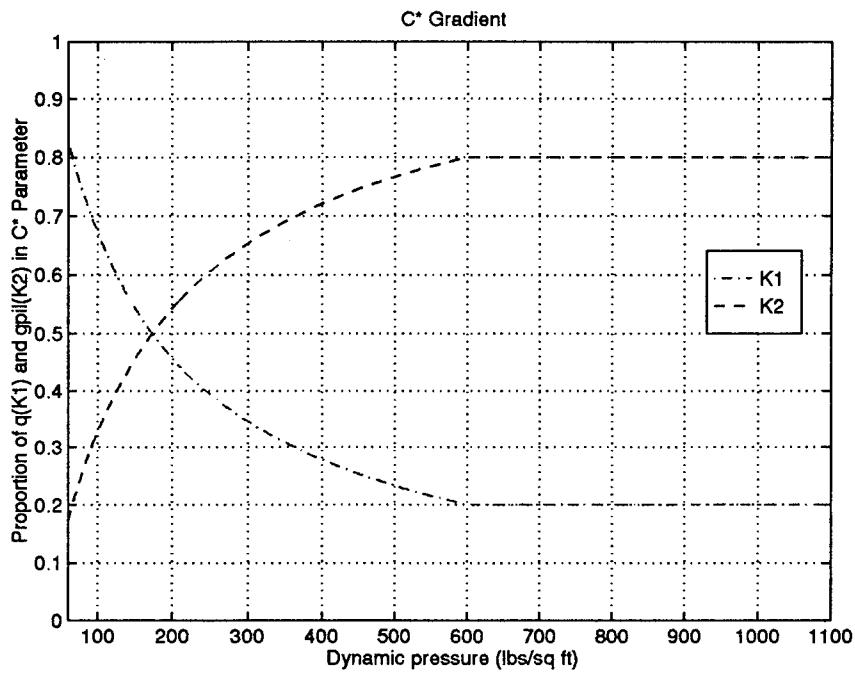


Figure 5.2 Allocation of q and g_{pi} in C^* Parameter versus \bar{q}

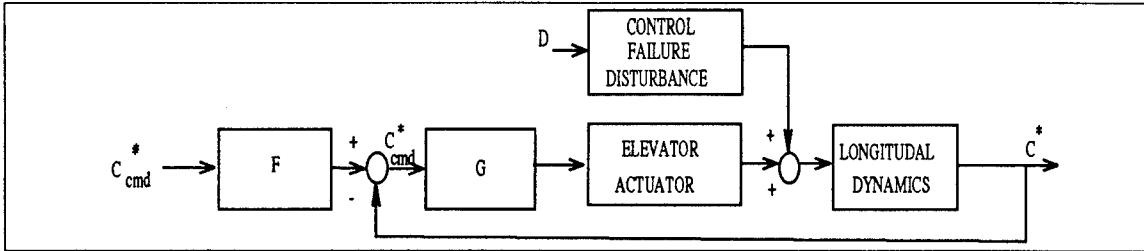


Figure 5.3 MIMO QFT Design Structure

With the inner loop question resolved, the C^* variable defined, and external disturbances added, the longitudinal QFT feedback structure with its associated 1X1 prefilter (**F**) and compensator (**G**) appears as shown in Fig. 5.3.

5.1.2 Longitudinal Specifications. There are four sets of specifications for the longitudinal channel that must be defined to continue with the QFT design procedure. The performance specifications for tracking, stability, and external disturbance rejection are developed in the following sections.

5.1.2.1 Tracking Specifications. The MILSTD 1797A defines time domain specifications for Level 1, 2, and 3 handling qualities in terms of pitch rate response to a step stick force input. The exact specifications for the onset delay (t_1), the onset rate (Δt), and the minimum damping ratio ($\frac{\Delta q_2}{\Delta q_1}$) can be found on Table 5.1 corresponding to Fig. 5.4. However, as Phillips determined, there are some difficulties in applying these time specifications to a full envelope flight control design involving an innovation as the feedback variable. These difficulties arise due to a couple factors. First, in this design the C^* , not pitch rate, variable is tracked. Second, the time domain specifications for Δt have a dependence on velocity V and thus change for each flight scenario. Finally, the time domain specifications must be transformed into the frequency domain for use in the QFT design.

| Parameter | Level 1 | Level 2 | Level 3 |
|---------------------------------|--|---|---|
| t_1 | $t_{1_{max}} \leq 0.12 \text{ s}$ | $t_{1_{max}} \leq 0.17 \text{ s}$ | $t_{1_{max}} \leq 0.21 \text{ s}$ |
| Δt | $\frac{9}{V} \leq \Delta t \leq \frac{500}{V}$ | $\frac{3.2}{V} \leq \Delta t \leq \frac{1600}{V}$ | No specification |
| $\frac{\Delta q_2}{\Delta q_1}$ | $\frac{\Delta q_2}{\Delta q_1} \leq 0.30$ | $\frac{\Delta q_2}{\Delta q_1} \leq 0.60$ | $\frac{\Delta q_2}{\Delta q_1} \leq 0.85$ |

Table 5.1 MILSTD Longitudinal Time Domain Tracking Specifications (Level 1,2,3)

Phillips circumvented the first of these difficulties by identifying that at low dynamic pressure, C^* is primarily composed of pitch rate (Fig. 5.2) and that the onset delay and rate are the dominating requirements at this pressure. Given this understanding, the MILSTD specifications for pitch rate response can be applied as an approximation to C^* specifications. Next, the floating specification issue is settled by properly selecting upper and lower limits on Δt . Finally, the last obstacle in the way of synthesizing QFT tracking bound models is overcome when reasonable approximations are made to translate the time domain specifications into the frequency domain.

Phillips' Level 1 tracking bound models (See Eqs. (5.3) and (5.4)) provide the foundation for the Level 2 and 3 models. Though a detailed explanation of these models can be found in the literature [15], some specifics are important to introduce. Phillips began with a natural frequency ω_n of 0.7. This ω_n was selected because most of the plant uncertainty for the healthy as well as the failed aircraft occurs at frequencies less than or equal to 1 rps, and this selection insures that the responses with the greatest overshoot and slowest

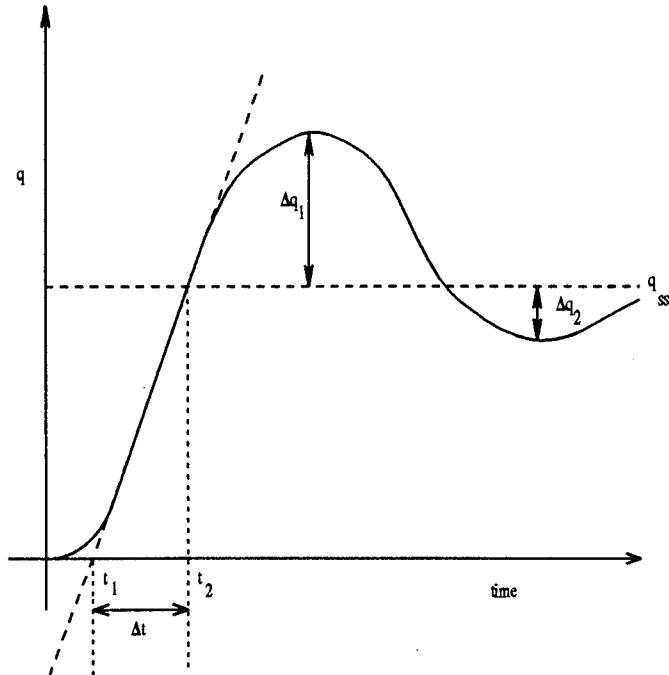


Figure 5.4 Step Response Used to Define Longitudinal Response Specifications

settling time are placed in the pilot's bandwidth. To satisfy the Level 1 t_1 requirement a pole is positioned at 2 rps, and then to insure a monotonically increasing separation between upper and lower tracking bounds δ_r another pole is added at 3 rps.

$$T_{R_U} = \frac{5(s + 0.7)^2}{(s^2 + 0.56s + 0.49)(s + 5)} \quad (5.3)$$

$$T_{R_{L1}} = \frac{6}{(s + 2)(s + 3)} \quad (5.4)$$

As Table 5.1 illustrates, the primary specification for the Level 2 and Level 3 models is the onset delay t_1 . Though the MILSTD develops specifications for Level 2 and Level 3 minimum damping ratios, only variations in the lower tracking bounds are considered in this research. It is assumed that if a healthy aircraft can not exceed the upper tracking bound, i.e. faster settling time, then a damaged aircraft with reduced control surface area can not either. Therefore the upper tracking bound serves as the model for all three levels of handling qualities. The lower tracking specifications, however, varies with each Level of handling qualities. The Level 2 (Eq. (5.5)) and Level 3 (Eq. (5.6)) models are

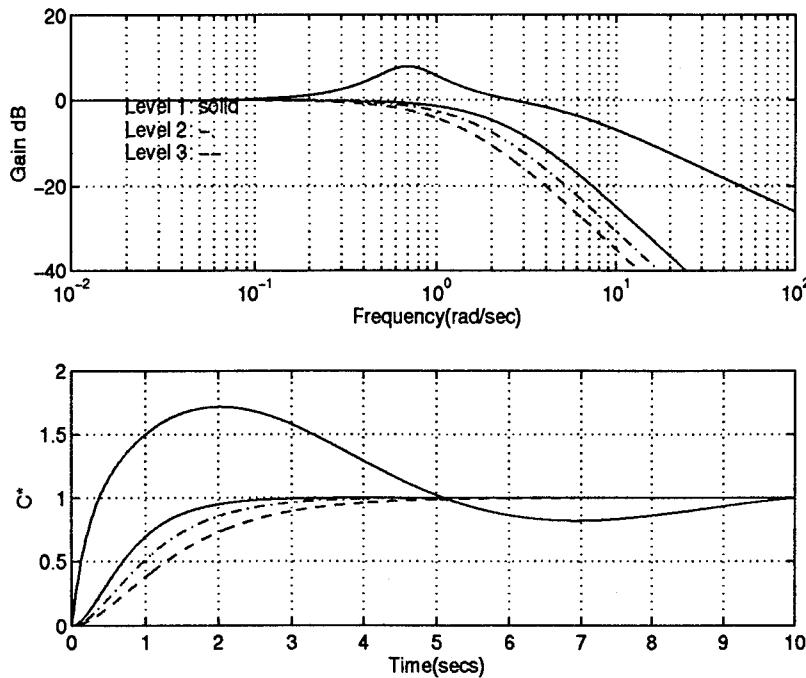


Figure 5.5 Step Input Time Response of QFT Upper and Lower Longitudinal Tracking Bound Models

synthesized by increasing the onset delay time for $T_{R_{L_1}}$ until these models approach the degraded specifications listed in Table 5.1. Manipulating $T_{R_{L_1}}$ to generate the other lower bounds guarantees satisfaction of the QFT requirement for a monotonically increasing δ_r as well. The time response for Level 1, 2 and 3 specifications can be found on Fig. 5.5 and in tabular form on Table 5.2.

$$T_{R_{L_2}} = \frac{3}{(s + 1.5)(s + 2)} \quad (5.5)$$

$$T_{R_{L_3}} = \frac{1.8}{(s + 1)(s + 1.8)} \quad (5.6)$$

5.1.2.2 Stability Specifications. The open loop frequency response of all plants, healthy as well as failed, must have a phase margin angle of at least 30 degrees and a gain margin of at least 6 dB as dictated by MILSTD 1797A stability specifications. These specifications are entered directly into QFTCAD to generate the stability bounds, and the 6 dB gain margin is verified visually using the stability validation function of QFTCAD.

| Model | t_1 | Δt | $\frac{\Delta g_2}{\Delta g_1}$ |
|------------|-------|------------|---------------------------------|
| T_{RU} | 0 | 0.215 | 0.255 |
| T_{RL_1} | 0.113 | 1.132 | overdamped |
| T_{RL_2} | 0.162 | 1.158 | overdamped |
| T_{RL_3} | 0.206 | 2.085 | overdamped |

Table 5.2 QFT Upper and Lower Tracking Bound Model Step Response Characteristics

5.1.2.3 External Disturbance Rejection Specifications. There is no specific external disturbance rejection specifications established in the MILSTD. Consequently, an arbitrary value of -20 dB is imposed on the design as discussed in Chap. II. This level of disturbance rejection is accepted with the understanding that further analysis of this specification is required later in the design.

5.1.2.4 Performance Benchmarks. The following longitudinal performance criteria must be satisfied to meet current F-16 flight control system performance.

1. Attain $25^\circ \alpha$, but do not exceed 30°
2. Achieve 9 g's but do not exceed 9.45 g's

Limiters prevent the aircraft from exceeding the 30° angle-of-attack and the 9.45 g load factor restrictions. Unfortunately, a limiter scheme is not implemented due to time restrictions experienced in this research. These limitations are necessary to maintain the integrity of the airframe and safety of the pilot, therefore before flight testing this design a limiting scheme should be developed.

5.1.3 Loaded and Effective Plants. The healthy plants are obtained from Phillips' research in the form of state-space **A** and **B** matrices. These 282 plants, representing three dimensions of plant parameter variation (altitude, airspeed, and center of gravity location), are subjected to the failure modeling process described in Chap. IV. The end result of this failure modeling routine is a failed aircraft plant for each healthy plant. Therefore the original 282 plants are consequently doubled for each failure level selected, where a failure level is defined in Chap. IV as a percentage loss in elevator area. Initially two plant sets are generated, one for the 15% damage level and another for the 25% damage level. These

two damage levels are selected based on Keating's work with the URV. [11] Keating found that a successful QFT design was achievable for an aircraft experiencing a 25% reduction in elevator surface area, thus 25% is chosen as a preliminary upper limit failure case. The 15% damage level is selected as a comparison to the 25% level, and as a backup plant set if a successful QFT design can not be implemented for the 25% failure case.

Given the C^* structure developed earlier in this chapter, as well as the aircraft and disturbance models, a *Matlab* macro is used to develop the associated QFT tracking and external disturbance transfer functions found in Eqs. (3.10) and (3.11). Since the longitudinal design represents a MISO case, the plant and external disturbance transfer function matrices are both 1x1 in dimension. These transfer functions are loaded into QFTCAD and the pole/zero cancellation routine is performed. This routine eliminates any pole/zero pairs within a 0.001 tolerance, and removes any dynamics greater than $10^{\pm 5}$ rps. After performing this cancellation process, the loaded plant models are placed in series with the fourth-order actuator model described in Chap. III to form the effective plants. The frequency response of these plants found in Fig. 5.6 confirms that the majority of plant uncertainty is constrained to frequencies less than 1 rps. The external disturbance plants demonstrate a similar property and are illustrated in Fig. 5.7.

5.1.4 Frequency Templates. After loading the plant cases into the QFTCAD program and generating the plant matrices \mathbf{P} , \mathbf{P}_e , and \mathbf{P}_D , the CAD 'Temp' option is selected and the frequency templates are automatically formed. The templates are identified over the frequencies given in Eq. (5.7).

$$\omega = 0.05, 0.075, 0.1, 0.25, 0.5, 0.75, 1, 3, 5, 7, 10, 13, 20, 25, 30, 50 \quad (5.7)$$

5.1.4.1 Healthy Aircraft Templates. One of the assumptions made in this research is that Phillips' LTI models incorporate all of the uncertainty inherent in the configuration variations he introduced. In his thesis there is a detailed explanation of how the number of boundary plants was increased to accommodate possible uncertainty found in plants that were not on the "edge of the envelope." This discussion is left to be reviewed by the interested reader. [15]

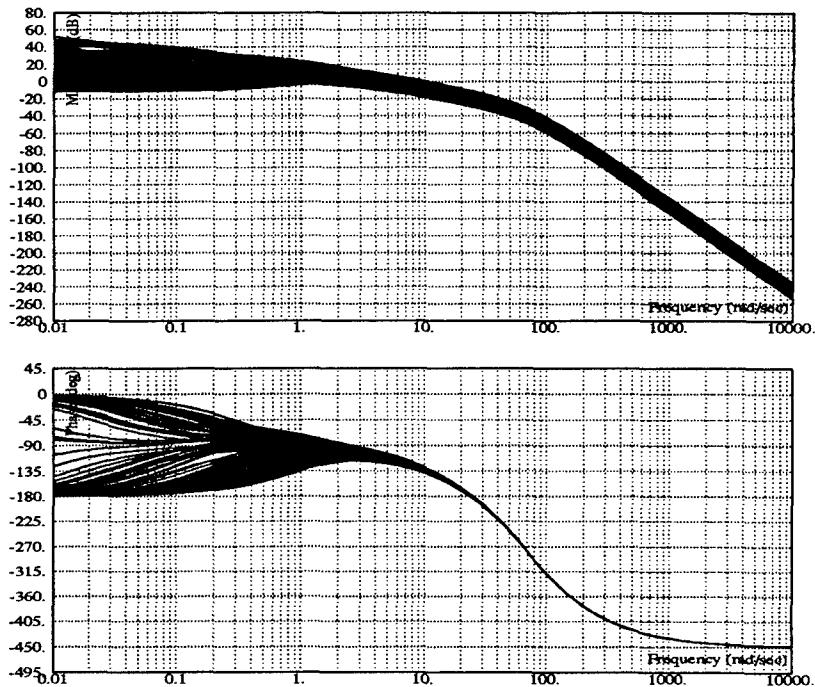


Figure 5.6 Frequency Response of Effective Plants P_e

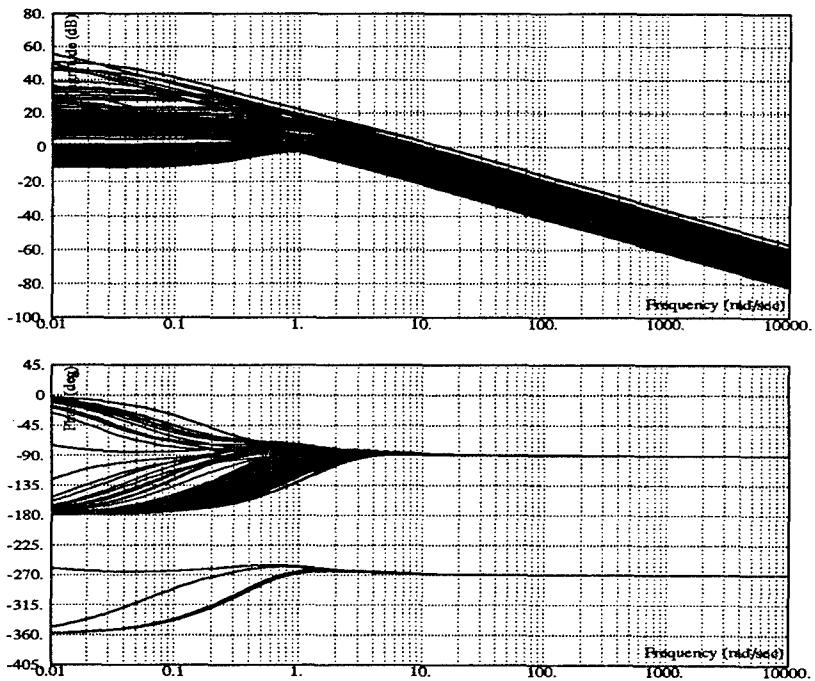


Figure 5.7 Frequency Response of Disturbance Plants P_D

Before proceeding with the analysis of the failure frequency templates, Phillips' healthy plant templates are employed as a benchmark to insure that there are no errors in the *Matlab* and *Mathematica* macros or in the plant files. The frequency templates afford an excellent opportunity to compare the two plant sets which should be identical at this point in the design. Unfortunately, upon comparing the healthy templates from Phillips' design with those generated in this design, several differences surfaced. After a thorough investigation of the transfer function formulation routines, a few discrepancies between the two designs are unearthed. The first, and most obvious, discrepancy involved the number of models employed to form the frequency templates. Following Phillips' inability to stabilize the 3 tank configuration over the entire subsonic flight envelope, he removed 83 plants from the original 282 in the healthy design set \mathcal{P} . This reduction in the number of plants caused Phillips' templates to become significantly smaller than the templates formed in this research. Also, a faulty *Matlab* linearization function known as 'linmod' was used in Phillips' research. This function is to blame for the second discrepancy in healthy frequency templates, and is explained further in Appendix E. After generating the C^* variable without this *Matlab* function the two plant sets were indistinguishable. Finally, it is decided to proceed with the plant templates (Figs. 5.8 and 5.9) developed in this research as the accurate healthy aircraft templates without the 3 tank configuration. A complete list of the flight condition/configuration data points used in the design is contained in Appendix B.

5.1.4.2 Failed Aircraft Templates. The frequency templates provide the first opportunity to determine the extent of control effector failures on the aircraft system. Figures 5.10 and 5.11 illustrate the failure effects at low frequencies ($\omega = 1$ rps). Holding frequency constant, the overall trend is for the templates to expand in a downward direction as the damage level increases. The 15% failure templates grew approximately 3 dB in magnitude and 2 degrees in phase, while the 25% templates increased approximately 5 dB in magnitude and 3 degrees in phase. Overall, the log magnitude and phase of template expansion appears to be proportional to control effector damage level.

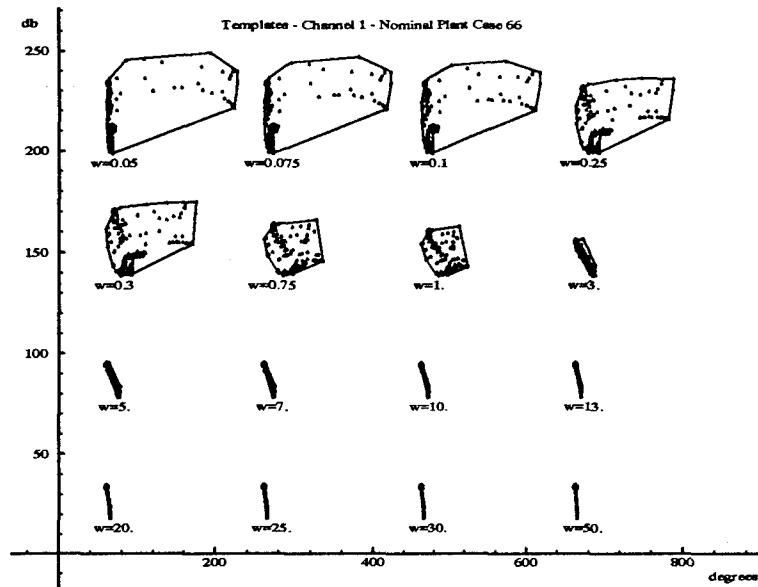


Figure 5.8 Healthy Aircraft Frequency Templates

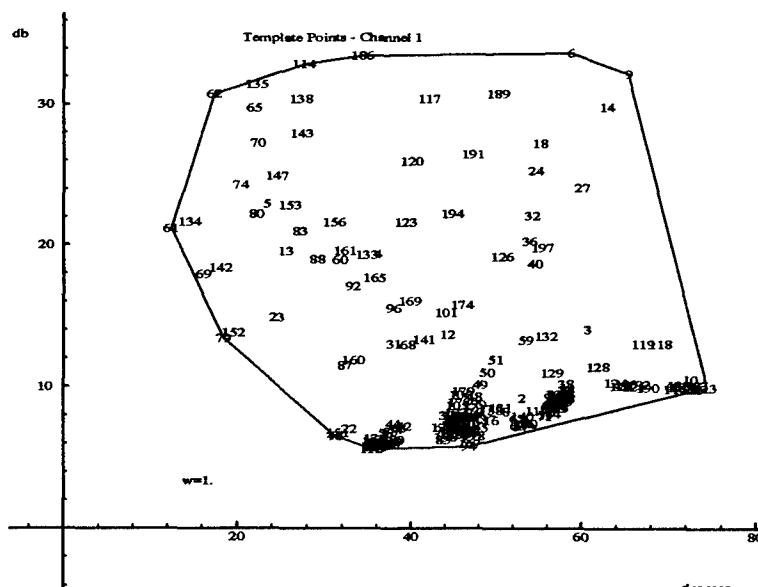


Figure 5.9 Healthy Aircraft Frequency Template for $\omega = 1 \text{ rps}$

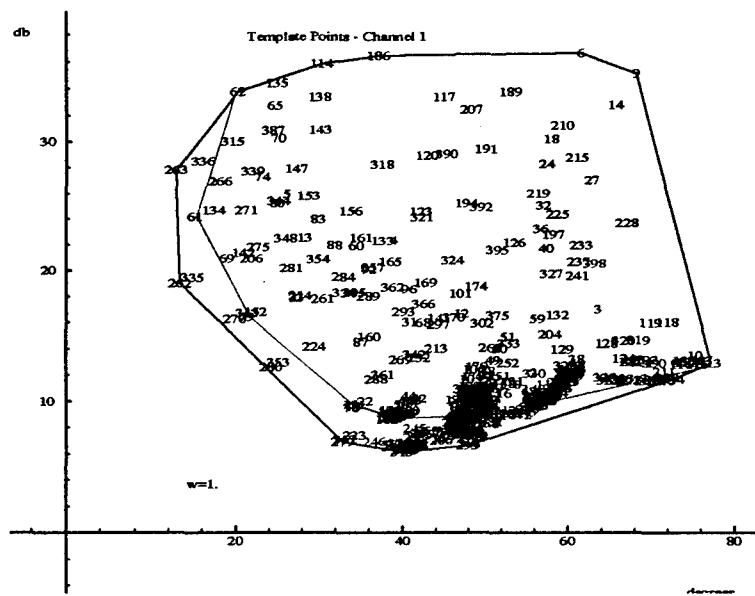


Figure 5.10 15% Horizontal Stabilizer Failure Frequency Template for $\omega = 1rps$

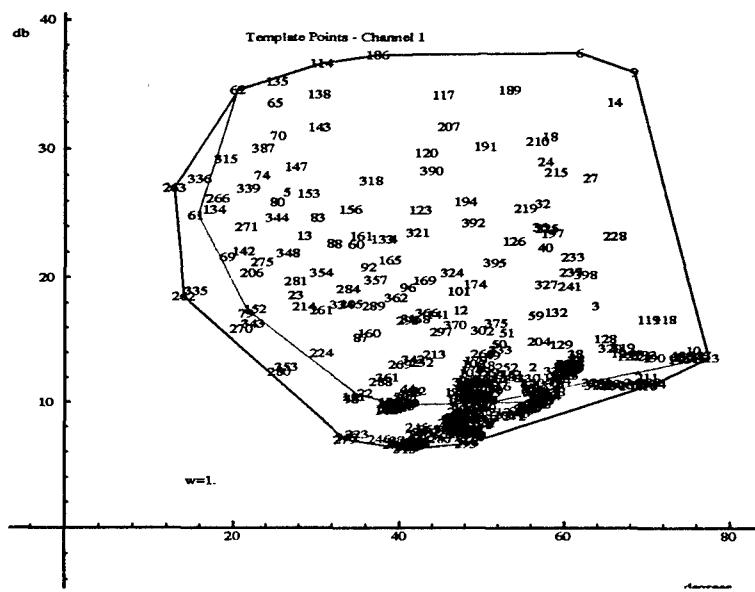


Figure 5.11 25% Horizontal Stabilizer Failure Frequency Template for $\omega = 1rps$

At higher frequencies, $\omega \geq 30\text{rps}$, the templates in Figs. 5.13 and 5.14 exhibit a dramatic increase in area when compared with the healthy aircraft template in Fig. 5.12. The low dynamic pressure plants, located on the bottom of the failure frequency templates, maintain a pattern similar to the low frequency plants in Fig. 5.10, while the high dynamic pressure plants, located on top of the frequency template, decrease in magnitude but increase in phase. It is very difficult to distinguish a pattern in these high frequency failure templates due to the large number of variables influencing their behavior. However, after closely examining the template data and plant generation process, some strong relationships become apparent. From a comparison of Figs. 5.12, 5.13 and 5.14 the failure templates exhibit a dependence on the damage level, as well as the C^* gradient. Because the high \bar{q} plants are primarily composed of normal acceleration, the high dynamic pressure plants increase in phase, and both the normal acceleration and pitch rate transfer functions only differ in their numerators, it appears that the zeroes of the normal acceleration plants are less effected by failures than the zeroes of the pitch rate transfer functions. Increasing the frequencies from 1 to 30 rps, the failed plants tend to rotate clockwise on the Nichols chart while decreasing in magnitude as the frequency increases. This swirl effect is illustrated in Fig. 5.15. To further support this relationship the 200 lbs/ft^2 plants which represent nearly an equal blend of pitch rate and normal acceleration feedback are located in the center of the failed templates and exhibit only a change in magnitude corresponding to the damage level. The swirl effect extends Phillips' innovation to the failure environment, and further emphasizes the importance of properly selecting the feedback variable in a robust aircraft design.

Overall, there is not a substantial difference in magnitude and phase between the 25% failure and 15% failure templates, therefore the 25% failure plant set is applied for the remainder of the longitudinal design. If a successful QFT design can not be implemented with this plant set, or if the time simulations involving the saturation nonlinearities create insurmountable stability problems, then the 15% failure plants will replace the 25% cases. The 25% failure plants combined with the healthy plants are identified in Fig. 5.16.

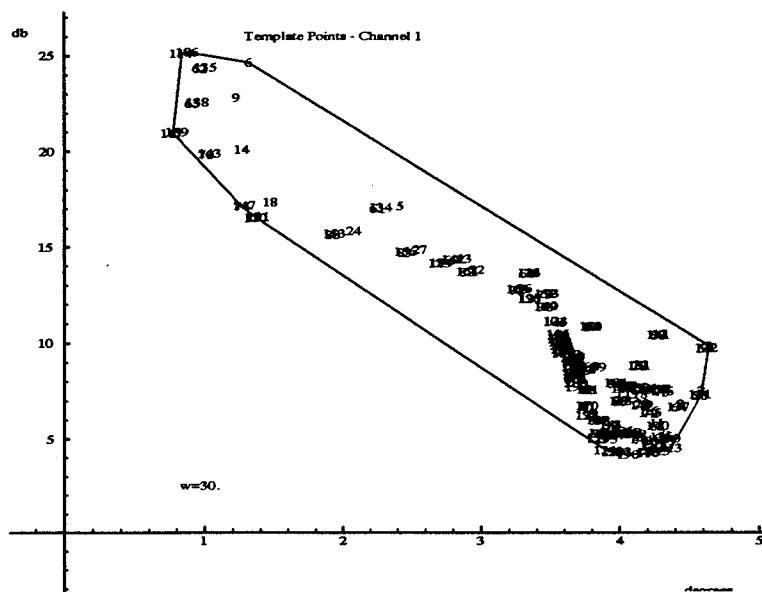


Figure 5.12 Healthy Aircraft Frequency Template for $\omega = 30\text{rps}$

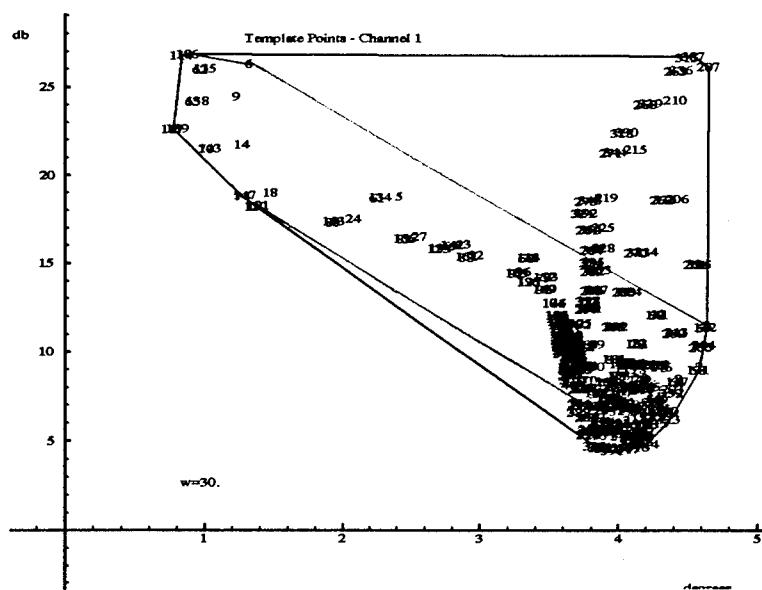


Figure 5.13 15% Horizontal Stabilator Failure Frequency Template for $\omega = 30rps$

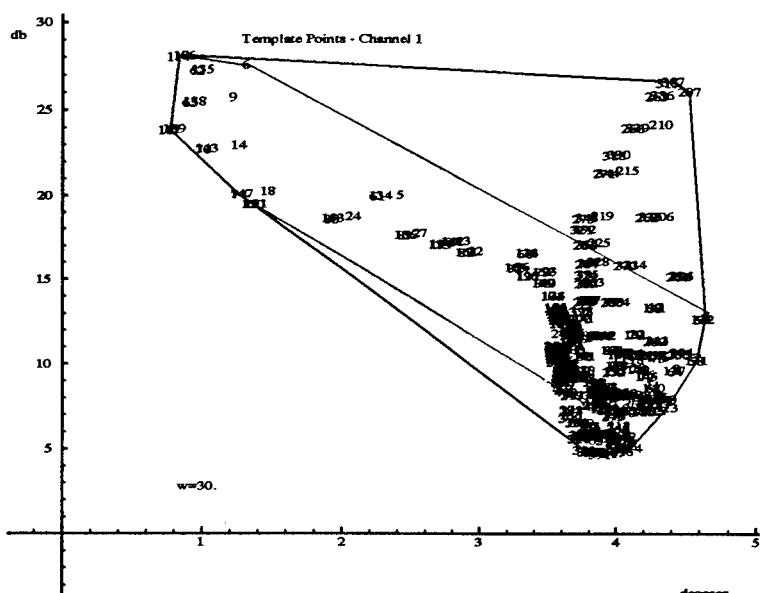


Figure 5.14 25% Horizontal Stabilator Failure Frequency Template for $\omega = 30rps$

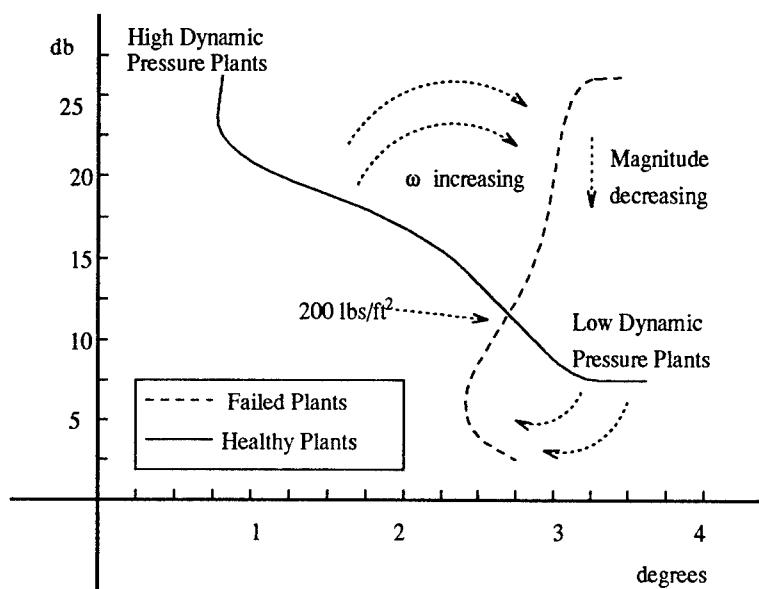


Figure 5.15 Illustration of High Frequency Failure Effects on QFT Frequency Templates

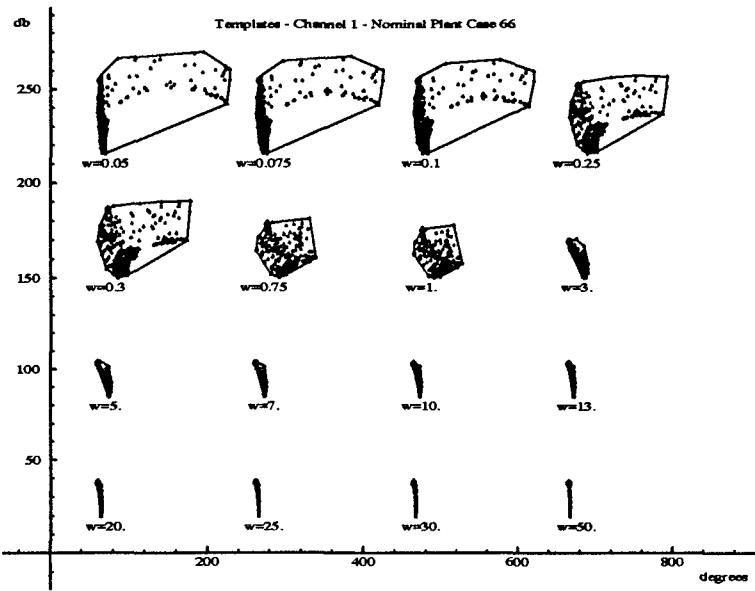


Figure 5.16 Plant Templates for VISTA Experiencing 25% Horizontal Stabilator Failure

5.1.5 QFT Generated Bounds. To continue with the generation of the QFT tracking and external boundaries, the nominal plant must be selected in accordance with the specifications outlined in Chap. II. The #66 plant (SRF plant model#70) is chosen as the nominal plant due to its location on top of the 30 rps frequency template.

5.1.5.1 Tracking Bounds. Figure 5.17 displays the tracking bounds for the 25% failure case. There are some important features of these tracking bounds that should be highlighted. The first, and probably most significant, feature effecting the design is that the tracking bounds reflect the increase in template size due to failures. Comparing the healthy tracking bounds and those generated for the failure cases, an increase in gain of approximately 5 dB is noticeable within the pilot's bandwidth. Second, though the tracking bounds form a valley permitting a reduced compensator gain, it is doubtful that this valley can be exploited in the design. Phillips' stability validation indicates that the healthy models require a significant increase in phase just to maintain stability at the lower frequency range of interest. Finally, the lower frequency range bounds roughly between 0.05 and 0.1 rps are particularly difficult to achieve, a finding not isolated to the failure cases.

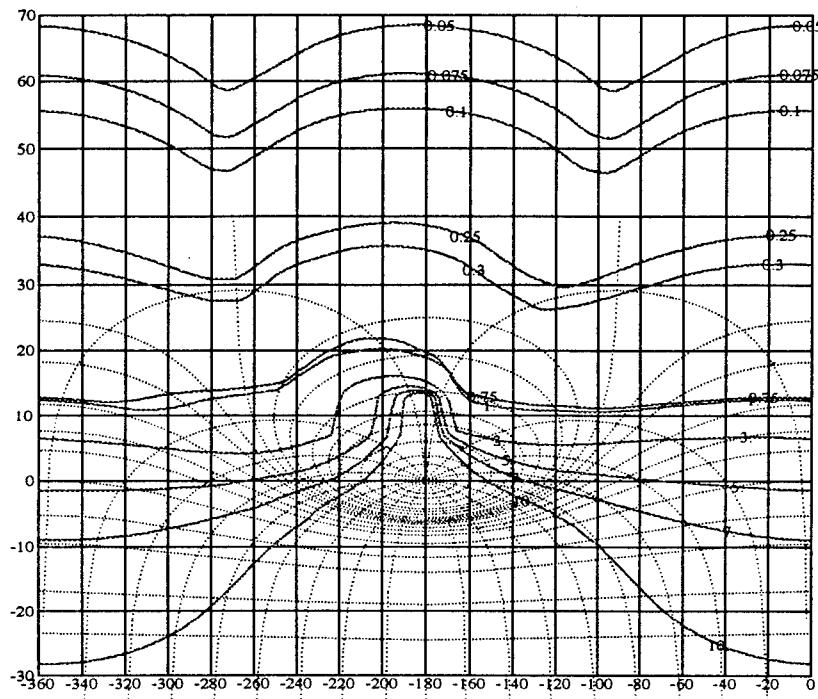


Figure 5.17 QFTCAD Tracking Bounds

5.1.5.2 External Disturbance Bounds. The external disturbance bounds are illustrated in Fig. 5.18. From this figure it is obvious that the external disturbance rejection bounds are virtually unachievable. As an example, to satisfy the external disturbance rejection bound at $\omega = 1$ an increase in gain of approximately 25 dB is required. Such a drastic increase in gain would certainly cause rate and deflection saturation problems later in the design, especially since Phillips design, which was concerned with only the healthy cases, experienced mild saturation under a significantly reduced system gain. Therefore, as a first attempt to solve this gain problem, a degraded specification of -11 dB is introduced and the bounds are regenerated. Unfortunately, this new specification does not substantially reduce the system gain necessary to clear the bounds. Next, the addition of an external disturbance input is reexamined, and an engineering compromise is made. By stating that the aircraft can not reject -20 dB of the disturbance input, this is equivalent to saying that the pilot may experience some effects of a 25% reduction in elevator surface area. Since the goal of this design is to construct a flight control system not an autopilot system, it is accepted that the pilot may have to apply some command inputs after a

failure occurs in order to maintain control of the aircraft. Finally, the compensator gain required to achieve tracking will also help minimize the effect of the external disturbance. This can be seen from analyzing Eq. (5.8) obtained from Eq. (2.2).

$$T_D(j\omega) = \frac{Y(j\omega)}{D(j\omega)} = \frac{P_D(j\omega)}{1 + G(j\omega)P(j\omega)} \quad (5.8)$$

If $|G(j\omega)P(j\omega)| \gg 1$ in the bandwidth of concern, then

$$T_D(j\omega) = \frac{Y(j\omega)}{D(j\omega)} \approx \frac{1}{G(j\omega)} = \frac{1}{K_G G'(j\omega)} \quad (5.9)$$

Thus, as seen on Eq. (5.9) any increase in K_G to achieve tracking reduces the effect of the external disturbance on the output. However, this explanation does not give the designer license to simply ignore the external disturbance problem, for an external disturbance can excite the bending modes of the aircraft or possibly cause the system to become unstable. Therefore, the refined external disturbance goal is to remove the disturbance bounds from consideration, and proceed with the development of the compensator G . Once the design is complete, an external disturbance rejection validation is examined and time simulations are run to determine the extent of the disturbance effects on the system.

5.1.6 Compensator Design. The three constraints, discussed in Chap. II, that are imposed on the compensator, combined with the deleterious effects of the fourth-order actuator model and the statically unstable F-16 model, represent a serious challenge in the QFT loop shaping process. Several design iterations are necessary to satisfy the required QFT bounds and develop the final compensator design in Eq. (5.10). A brief description of the design process follows.

Since the nominal plant P_o is Type 0, the compensator must contain a pole at the origin for $L_o = P_o G$ to be Type 1. Thus, the loop shaping process is initialized with $L_{o_1} = \frac{1}{s} P_o = G_1 P_o$. Two zeros and an additional pole are added to G_1 yielding the final compensator design in Fig. 5.19. It is important to note that the most restrictive aspect of this process is circumventing the stability contour with a minimal order compensator. The two zeros are positioned to achieve the maximum possible increase in phase. Though

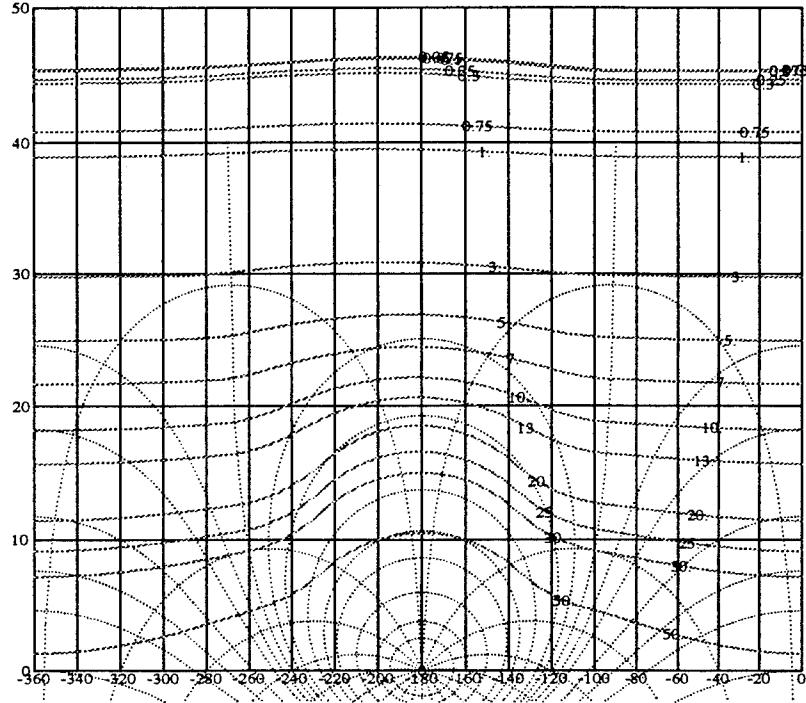


Figure 5.18 QFTCAD External Disturbance Bounds

it appeared during the loop shaping that the zero at 2.3 rps can be shifted to a lower frequency allowing the system a sufficient increase in phase to clear the top of the M_L contour, the step response of the system became increasingly more intolerable as the zero was reduced in frequency. This is significant because it demonstrates a possible upper limit on the level of uncertainty this design can incur and still achieve the required the stability and tracking specifications.

The final longitudinal compensator G is:

$$G = \frac{4.45(s + 2.3)(s + 12.5)}{s(s + 43)} \quad (5.10)$$

5.1.7 Prefilter Design. The goal of the prefilter design is to position the compensated system between the upper and lower tracking bounds now that the system has the necessary robustness. Initially, a simple pole is placed at 3.5 rps to insure that the system provides the adequate response over the pilot's bandwidth. The final prefilter design incorporates a zero to shift some higher frequency plants within the tracking boundaries. The

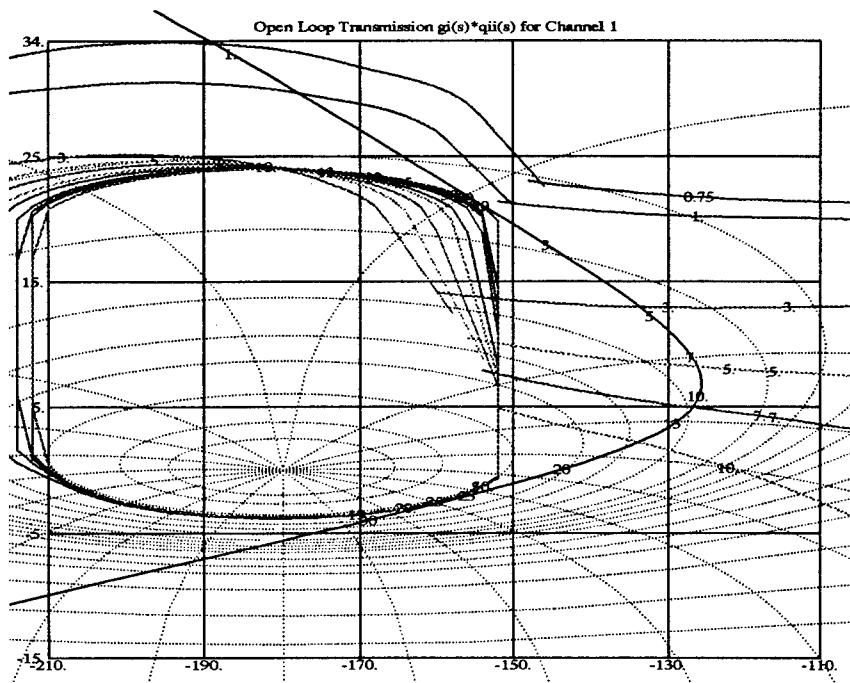


Figure 5.19 QFTCAD Nominal Loop Shaping

QFTCAD prefilter Nichols chart shown in Fig. 5.20 illustrates that the system satisfies the tracking boundaries within the bandwidth of interest.

$$F = \frac{0.25(s + 6)}{s + 1.5} \quad (5.11)$$

5.2 Time Simulations

The purpose of the time simulations is to demonstrate that the compensated system satisfies the various longitudinal time domain specifications. For these simulations a sample of 20 time responses is displayed over the specific \bar{q} range identified on each figure. This sampling is based on analyzing the data in Appendix C for all 398 LTI plant cases and discerning those cases that comprise the limits of the overall time responses. An alternative method of validating this selection of plant cases is to analyze the plants that lie on a boundary of frequency templates. The 20 plant cases selected via the time response data should correspond exactly to these boundary plants. To further discriminate the impaired and unimpaired plant cases, the failed plants are denoted by dashed lines on the figures,

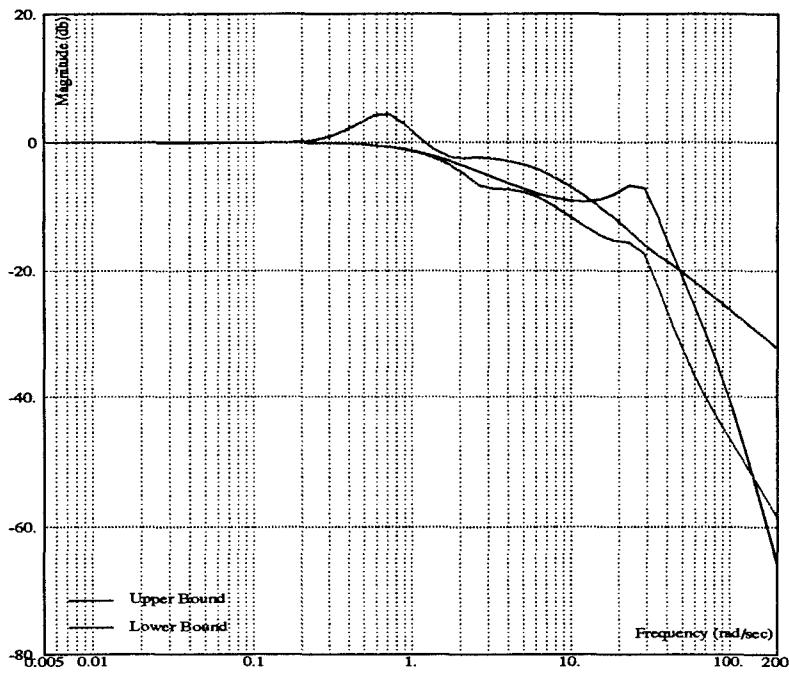


Figure 5.20 QFTCAD Prefilter Design

and the healthy plants are denoted by the solid lines. This line convention is maintained throughout this report.

5.2.1 C^* Tracking Responses. Proceeding with a worst case design scenario, Figs. 5.21 and 5.22 represent the unit step tracking responses of the low \bar{q} compensated system. Also, the MILSTD flying quality levels are superimposed on the C^* tracking responses to simplify performance evaluation. As expected, the failed plants exhibit less damping and increased onset delay than the healthy plants. It is apparent from these figures that the healthy aircraft plants satisfy Level 1 flying qualities specifications while the failed aircraft meet at least Level 2 specifications. In addition, the angle of attack(α) response displays the effect of the elevator failure since most of the failed plants do not attain half of the maximum healthy aircraft's α . The C^* blending is easily identifiable within the q and g_{pil} time responses as well. It is important to remember that the C^* is the feedback variable and not pitch rate q . This explains why neither the pitch rate or the normal acceleration at the pilot's station g_{pil} responses settle to the same steady state value. Finally, the failure plants dominate the elevator deflection authority but do not

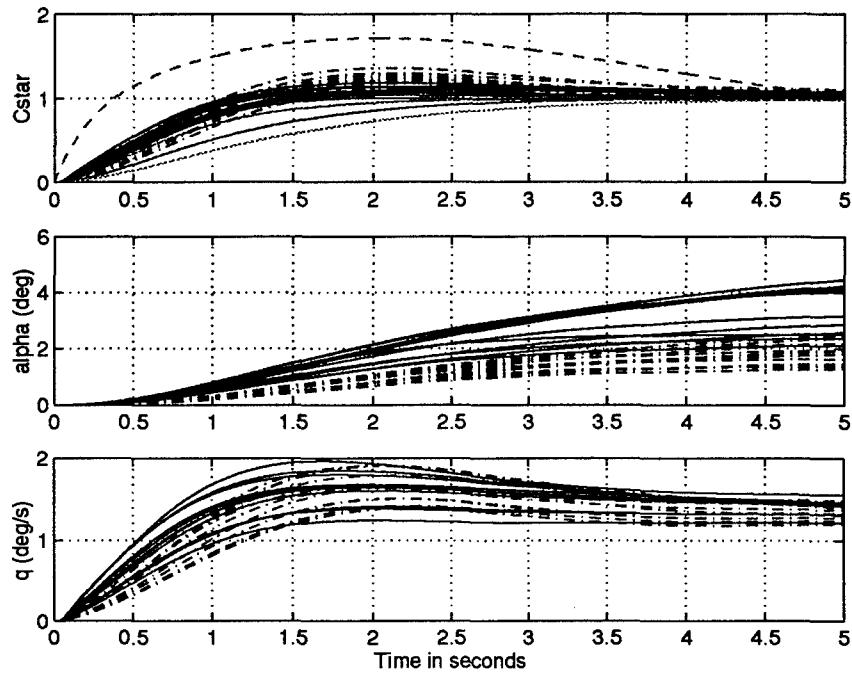


Figure 5.21 Unit C^* Step Response of Compensated System, Healthy Aircraft and 25% Stabilator Failure Plants ($\bar{q} < 200 \text{ lbs}/\text{ft}^2$) [1 of 2]

have a significant impact on the elevator rate. All of these plots are further supported by the tabular data found in Appendix C.

Figures 5.23 and 5.24 illustrate the longitudinal design dependency on \bar{q} . The ballooning witnessed for the low \bar{q} failed plants in Fig. 5.21 is non-existent for the higher energy plants. All of the high \bar{q} responses, healthy as well as failed, meet Level 1 specifications. The pitch rate response is noticeably faster, the g loading is nearly doubled and the demand placed on the elevator authority is reduced by approximately 3 degrees in comparison to the low \bar{q} plants.

5.2.2 Maximum Command Gradient. The unit step simulations generate the data necessary to determine whether the system satisfies the time domain Level 1 or 2 specifications. These simulations also provide an opportunity to calculate the maximum command input that can be applied to the system without causing rate and deflection saturation. Phillips employed the following relations to construct such a maximum C^*

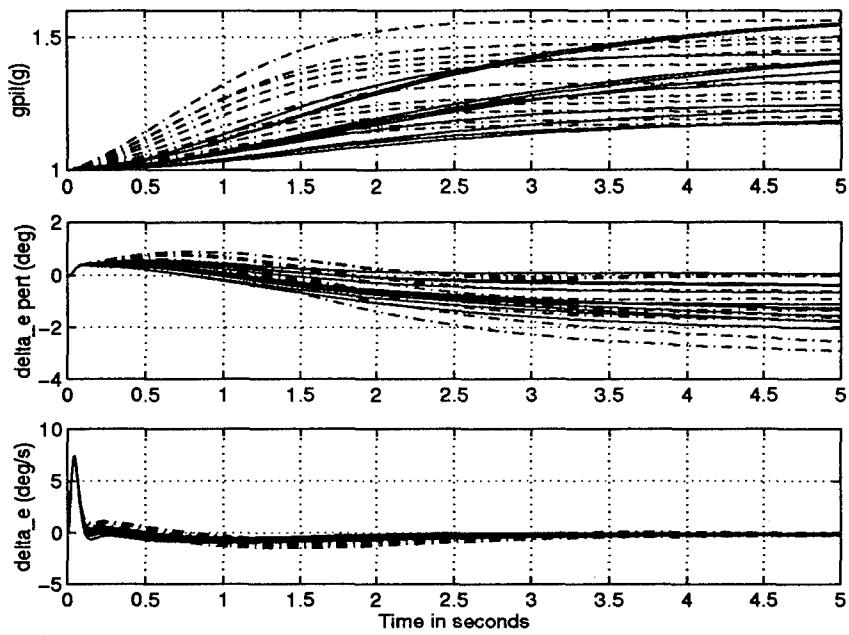


Figure 5.22 Unit C^* Step Response of Compensated System, Healthy Aircraft and 25% Stabilizer Failure Plants ($\bar{q} < 200 \text{ lbs}/\text{ft}^2$) [2 of 2]

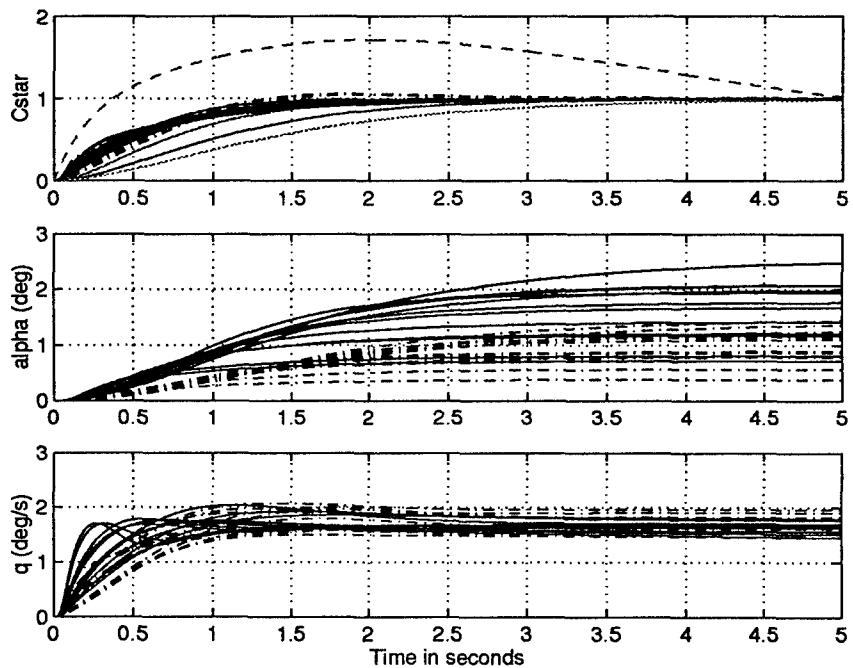


Figure 5.23 Unit C^* Step Response of Compensated System, Healthy Aircraft and 25% Stabilizer Failure Plants ($\bar{q} > 200 \text{ lbs}/\text{ft}^2$) [1 of 2]

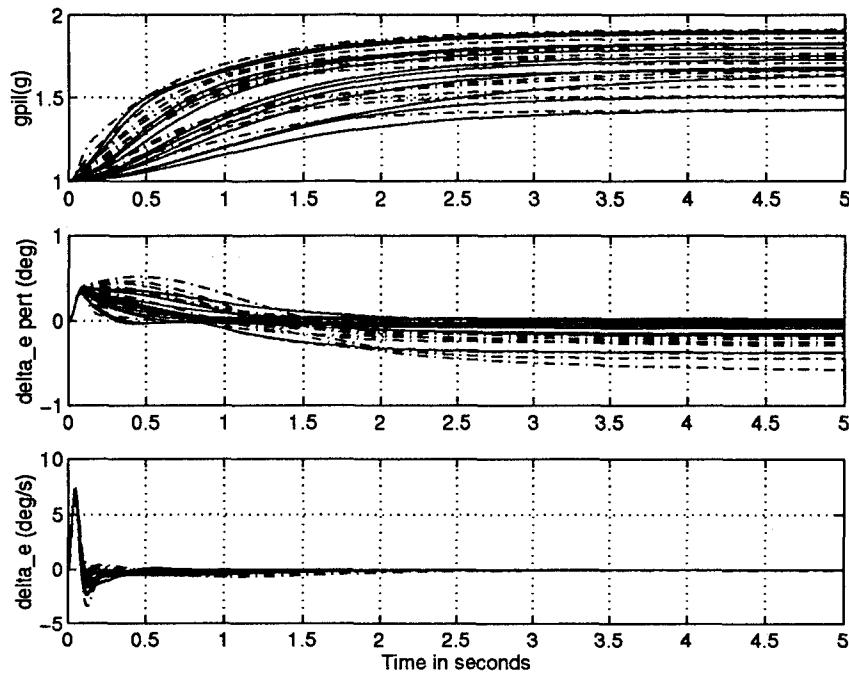


Figure 5.24 Unit C^* Step Response of Compensated System, Healthy Aircraft and 25% Stabilizer Failure Plants ($\bar{q} > 200 \text{ lbs}/\text{ft}^2$) [2 of 2]

command profile given the unit step responses:

$$\left[\begin{array}{l} \frac{20 - \text{trim}_{elev}}{\max\{\delta_{elev(pert)}\}}, \text{ for } \delta_{elev(pert)} > 0, \\ \text{and} \\ -\frac{20 + \text{trim}_{elev}}{\min\{\delta_{elev(pert)}\}}, \text{ for } \delta_{elev(pert)} < 0 \end{array} \right] \quad (5.12)$$

$$\frac{60}{\dot{\delta}_{elev(\max)}} \quad (5.13)$$

$$\frac{25 - \alpha_{trim}}{\alpha_{pert(\max)}} \quad (5.14)$$

$$\frac{8}{g_{pil(\max)}} \quad (5.15)$$

As an additional constraint there is one healthy plant and one failed plant for each \bar{q} point. Therefore, the minimum of Eqs. (5.12) and (5.13) and the maximum of Eqs. (5.14) through (5.15) for each \bar{q} case is employed in the development of the boundaries. This procedure generates the worst case restrictions on the aircraft. The maximum command

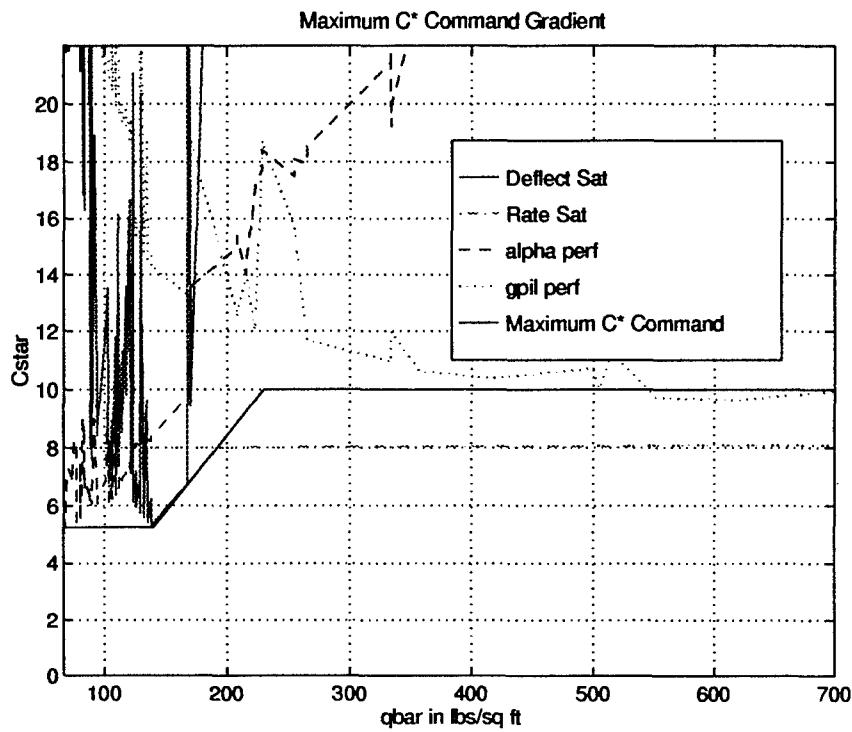


Figure 5.25 Maximum C^* Command Profile

gradient must fit under the saturation boundaries given by Eqs. (5.12) and (5.13) while simultaneously maintaining a level greater than the performance boundaries represented by Eqs. (5.14) and (5.15). The command profile is found in Fig. 5.25. It is apparent from this figure that the performance boundaries can not be achieved without rate saturating the actuators. It is also apparent that the g_{pil} performance specifications are meaningless and unachievable for the low \bar{q} range, while the alpha performance specifications become unachievable for the high \bar{q} plants. Furthermore, after flight testing his control system on the SRF nonlinear simulator, Phillips admitted that his command profile, which avoids both rate and saturation limits over the entire \bar{q} range, was probably 'too conservative.' [6] Ultimately, some compromises are required to balance control effector saturation and performance specifications. Since the rate saturation boundaries prove to be the limiting factor, they are effectively ignored, while the alpha performance specifications are deemed valid for the plants under $200 \text{ lbs}/\text{ft}^2$ and the g_{pil} specifications are valid for plants in excess of $200 \text{ lbs}/\text{ft}^2$.

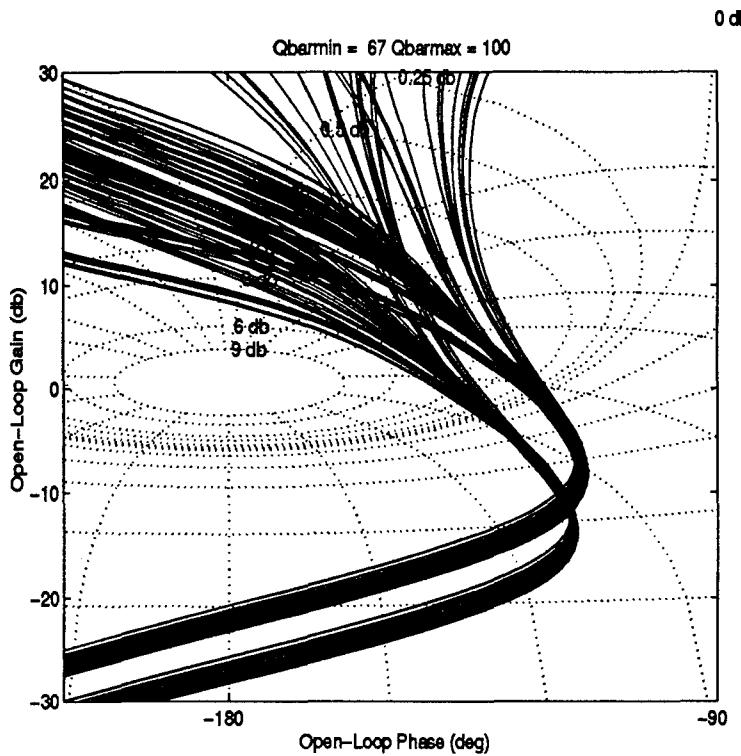


Figure 5.26 Nichols Chart of low \bar{q} Plants

When the rate and deflection saturation nonlinearities are added to the design, the system becomes unstable for several plants within the \bar{q} range of 100 to 150 lbs/ft^2 . To stabilize the system two courses of action are presented. Either gain scheduling can be introduced into the longitudinal system to adjust the demand on the elevator over the range of dynamic pressure, or the maximum command gradient can be reduced over this low \bar{q} range. The first course of action is found to be unacceptable since the plants causing the most difficulty are the low \bar{q} plants and they already define the top of the stability contour(see Fig. 5.26). The only plants that can be reduced in gain are the high \bar{q} plants and they are already acceptable. The second course of action proves to be more fruitful. After some trial and error, the rate saturation limits could be exceeded while the deflection saturation limits, especially in the low \bar{q} could not. If the deflection saturation limits are exceeded the VISTA becomes unstable. The final maximum command profile is reduced slightly in the low \bar{q} range, and the stability problems dissipate.

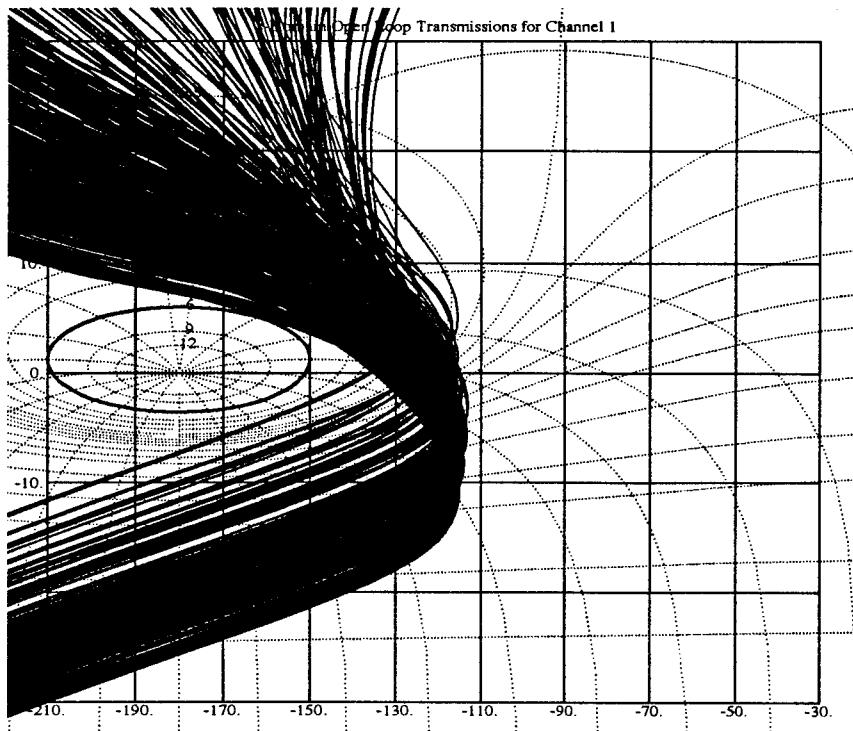


Figure 5.27 QFTCAD Stability Validation

5.3 Design Validation

As the final step in the design process, QFTCAD is utilized to verify that the system satisfies the frequency and time domain stability, tracking, and external disturbance specifications.

5.3.1 Stability Validation. Since the QFT design process is based on the manipulation of one nominal plant, it is necessary to guarantee that all 398 plants (199 healthy + 199 failed) meet the 30 degree phase margin and 6 dB gain margin stability requirements before concluding the design. As indicated on Fig. 5.27 all of the plants both healthy and failed meet the stability bounds, hence one of the major design goals is accomplished.

5.3.2 Tracking Validation. Though the lower frequency bounds can not be achieved during the loop shaping process, the tracking responses within the pilot's bandwidth met Level 1 and 2 specifications as seen in Fig. 5.28.

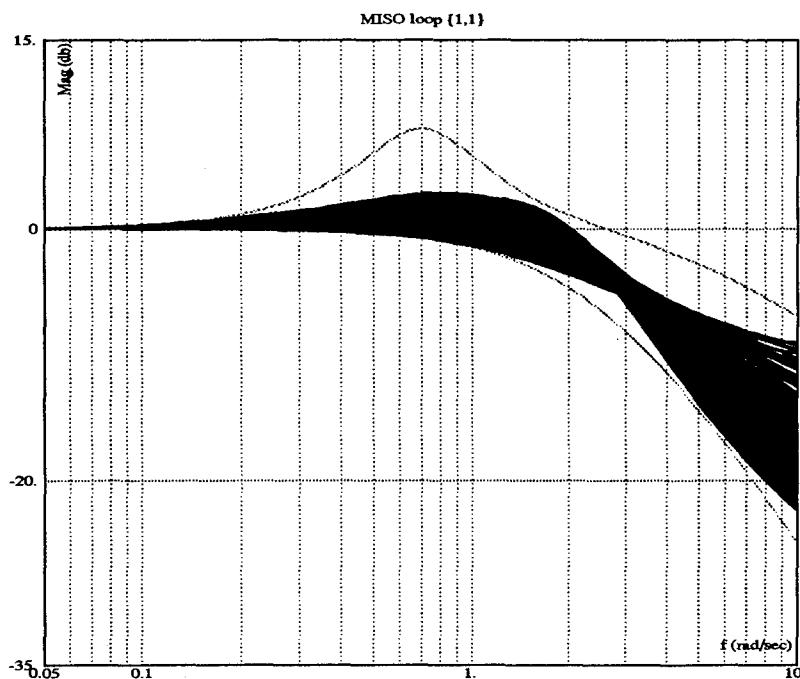


Figure 5.28 QFTCAD Tracking Validation

5.3.3 External Disturbance Rejection Validation. Unfortunately, the system shown in Fig. 5.29 does not exhibit the overall level of external disturbance rejection initially mandated. The problem plants represented by those exceeding the 0 dB limit at 2 rps and those exceeding the -11 dB limit at 30 rps, are identified as the low dynamic pressure failure plants. The external disturbance simulations are necessary to determine if these trouble plants can be controlled by a human pilot.

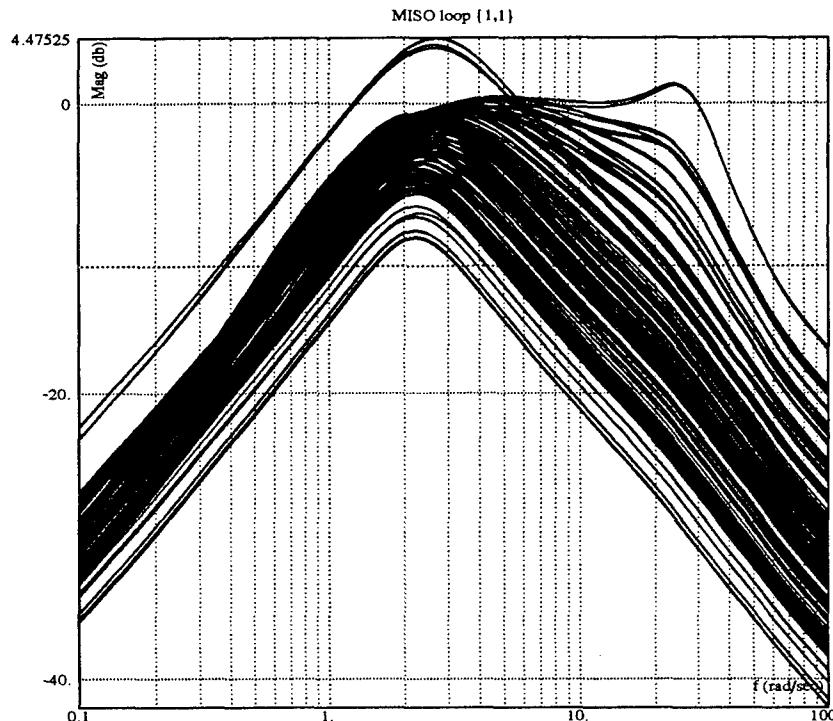


Figure 5.29 QFTCAD Disturbance Rejection Validation

5.3.4 Time Domain Validation.

5.3.4.1 C^* Tracking Responses. The compromise between performance for the healthy aircraft and stability for the failed aircraft is clearly seen in the low \bar{q} simulations found in Figs. 5.30 and 5.31. The healthy aircraft can only achieve 25° of α for approximately half of the plant cases, while the elevator (δ_e) is driven to its maximum deflection by the failure cases. The healthy plants also display significantly less onset delay and overshoot than the failed plants, yet the failed plants are still within the Level 2 flying qualities specifications supported by the tabular data in Appendix C. These effects demonstrate that the compensator allows the failed plants to saturate the elevator deflection, while simultaneously achieving nearly nominal performance by a majority of the healthy plants. Hence another major thesis goal is satisfied.

The dynamic pressure (\bar{q}) has the most substantial effect on the system responses of any of the plant parameters introduced in this design, and this fact is clearly illustrated in the comparison of Figs. 5.30 and 5.31 with Figs. 5.32 and 5.33. The performance criteria

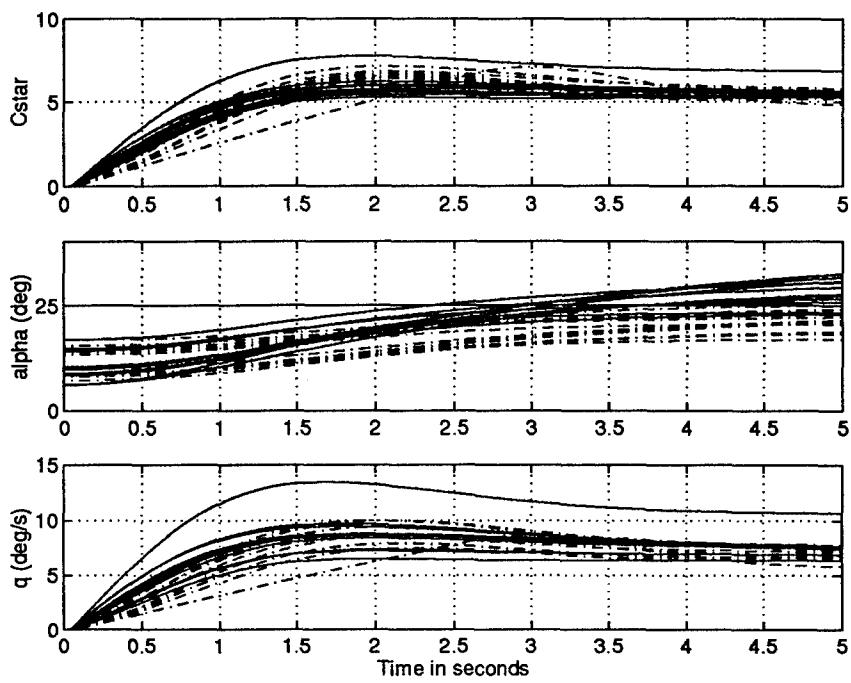


Figure 5.30 Maximum C^* Step Response of Compensated System, Healthy Aircraft and 25% Stabilizer Failure Plants ($\bar{q} < 200 \text{ lbs}/\text{ft}^2$) [1 of 2]

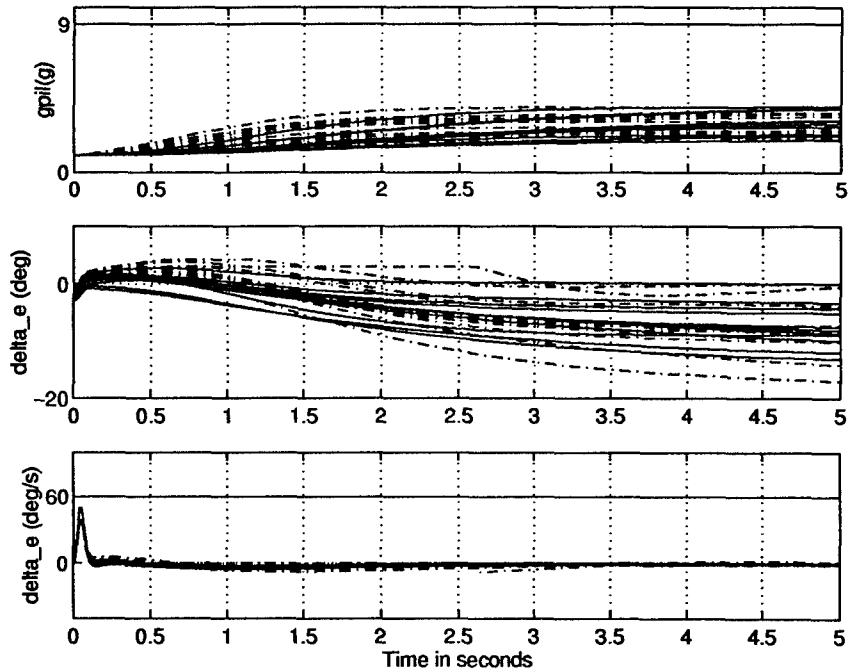


Figure 5.31 Maximum C^* Step Response of Compensated System, Healthy Aircraft and 25% Stabilizer Failure Plants ($\bar{q} < 200 \text{ lbs}/\text{ft}^2$) [2 of 2]

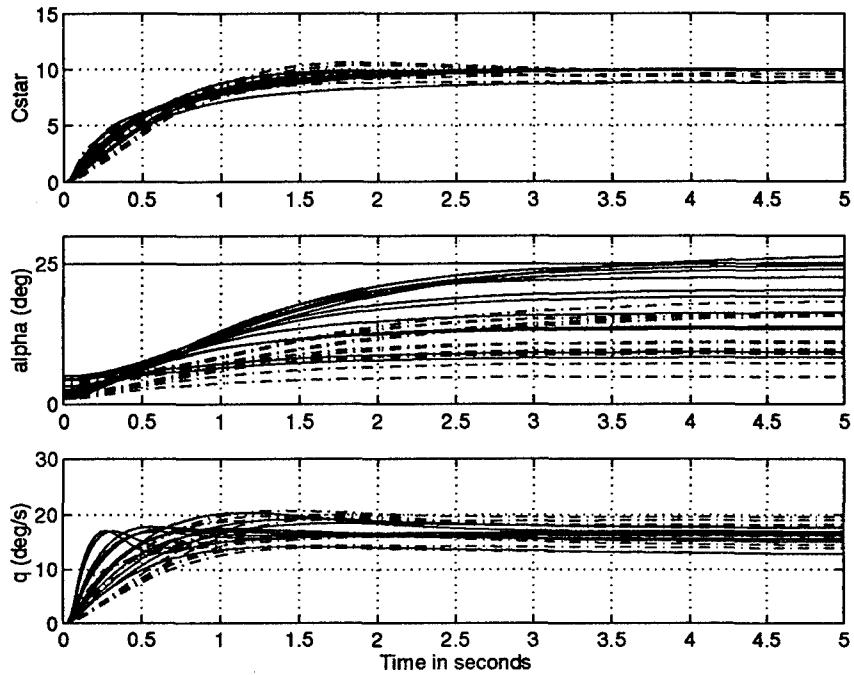


Figure 5.32 Maximum C^* Step Response of Compensated System, Healthy Aircraft and 25% Stabilizer Failure Plants ($\bar{q} > 200 \text{ lbs}/\text{ft}^2$) [1 of 2]

focus shifts away from meeting 25° of α for the low \bar{q} plants and towards meeting the 9 g's at the pilot station for the high \bar{q} plants. The majority of healthy plants either meet or exceed the g loading benchmark, while the majority of failed plants are slightly lower than the 9 g benchmark. Furthermore, there is significant dynamic pressure to generate the pitching moment with much less deflection of the elevator both for the failed and healthy plant cases. Moreover, saturating the elevator rate does not cause the same stability problems experienced when deflecting the elevator to saturation. Thus, the more aggressive maximum command profile proves to be beneficial in satisfying the required benchmarks.

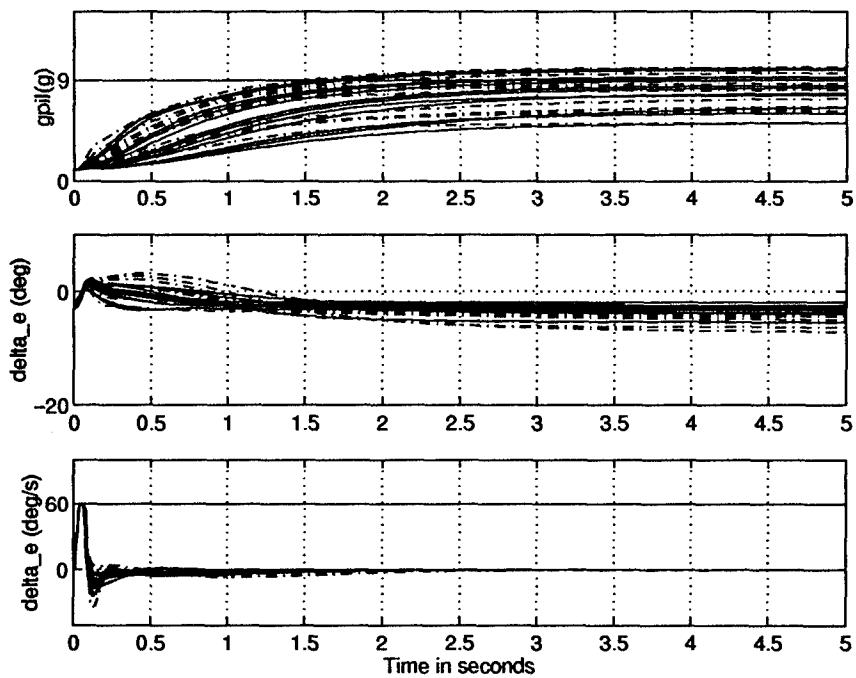


Figure 5.33 Maximum C^* Step Response of Compensated System, Healthy Aircraft and 25% Stabilizer Failure Plants ($\bar{q} > 200 \text{ lbs}/ft^2$) [2 of 2]

5.3.4.2 Disturbance. On the list of design criteria that are of vital importance to the system, the disturbance responses ranked the lowest. Keating modeled the longitudinal disturbance to reflect the change in trim due to a reduction in the elevator area. There are two goals in this disturbance analysis. First, the system must maintain stability, and, second, C^* must settle within the 5 second time period of interest. As the data found in Appendix C.5 and the disturbance responses for both low and high dynamic pressure found in Figs. 5.34 through 5.37 can attest both of these design criteria are achieved. In addition the maximum disturbance input caused a 0.80 g load and 10 deg/sec pitch rate change in the aircraft state. Both worst case scenarios can be countered by a human pilot and do not represent significant threats to the stability of the aircraft. Finally though the actuator rate limits are exceeded for the higher \bar{q} plants found in Fig. 5.37, the crucial deflection limits are not exceeded by either high or low \bar{q} plant cases, hence this degraded level of external disturbance is accepted as a consequence of designing a fault tolerant flight control system.

5.4 Longitudinal Design Summary

This chapter examines the complete longitudinal QFT design process including the development of the QFT structure, tracking model generation, frequency template failure analysis, compensator design and simulation evaluation. The first step in the design procedure is to fabricate the QFT feedback structure. In this design an innovation is applied as the feedback variable. The purpose of this innovation, known as C^* , is to combine pilot preference and engineering expertise in the formulation of a realistic FCS for the VISTA F-16. Though C^* more accurately reflects the pilot's tracking tendencies, the MILSTD only provides specifications for traditional pitch rate tracking. Approximations are necessary to translate the pitch rate tracking specifications to C^* and the onset rate t_i emerged as the dominant specification. With the tracking requirements set, the other stability and performance criteria are taken directly from the applicable requirements. The longitudinal design plant set \mathcal{P} is generated by *Matlab* macros to represent plant parameter variations over a range of altitude, airspeed, center of gravity, and of course control effector failure cases. Through the QFTCAD program the frequency templates are then formed, affording the

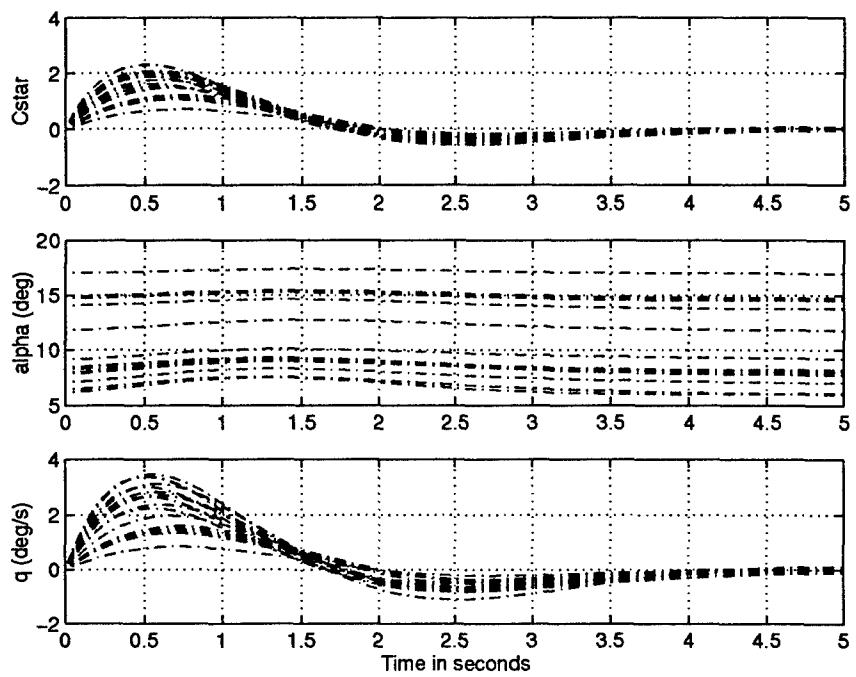


Figure 5.34 Disturbance Unit Step Response of Compensated System, 25% Stabilator Failure Plants ($\bar{q} < 200 \text{ lbs}/\text{ft}^2$) [1 of 2]

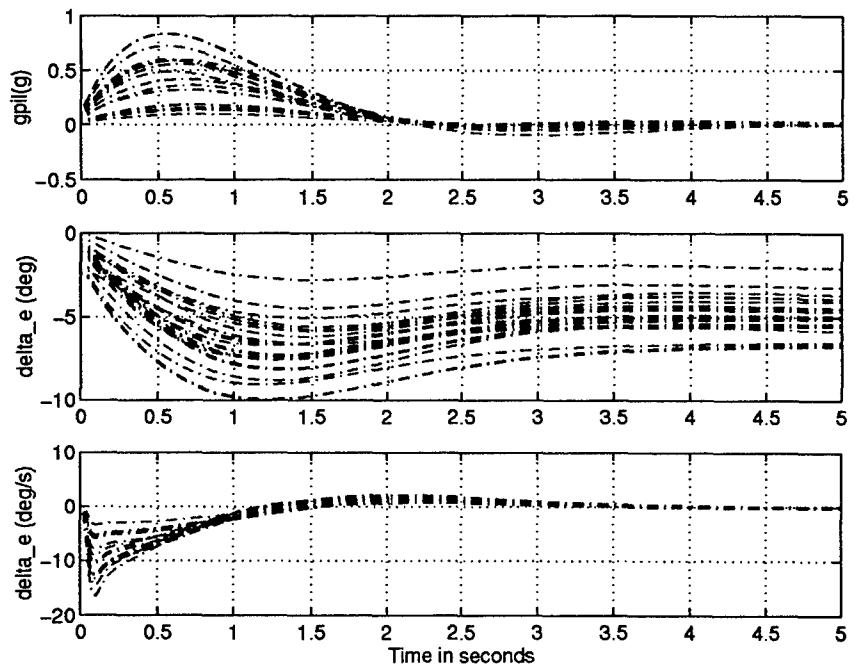


Figure 5.35 Disturbance Unit Step Response of Compensated System, 25% Stabilator Failure Plants ($\bar{q} < 200 \text{ lbs}/\text{ft}^2$) [2 of 2]

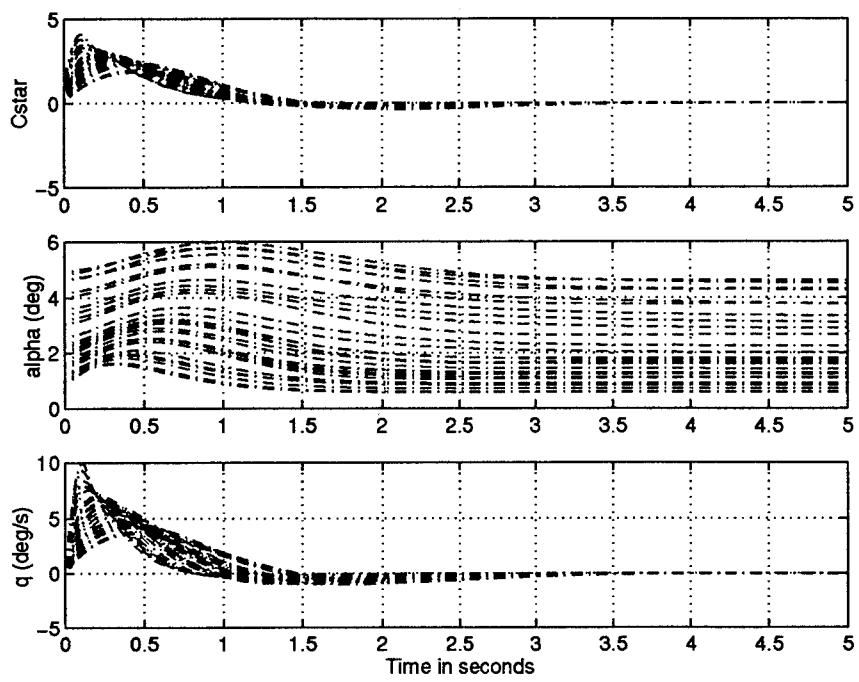


Figure 5.36 Disturbance Unit Step Response of Compensated System, 25% Stabilator Failure Plants ($\bar{q} > 200 \text{ lbs}/\text{ft}^2$) [1 of 2]

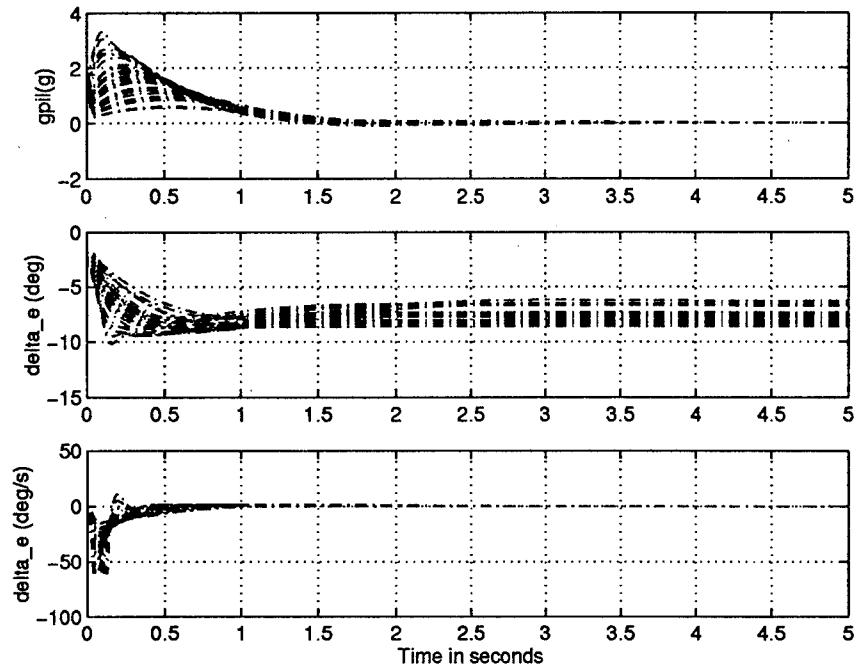


Figure 5.37 Disturbance Unit Step Response of Compensated System, 25% Stabilator Failure Plants ($\bar{q} > 200 \text{ lbs}/\text{ft}^2$) [2 of 2]

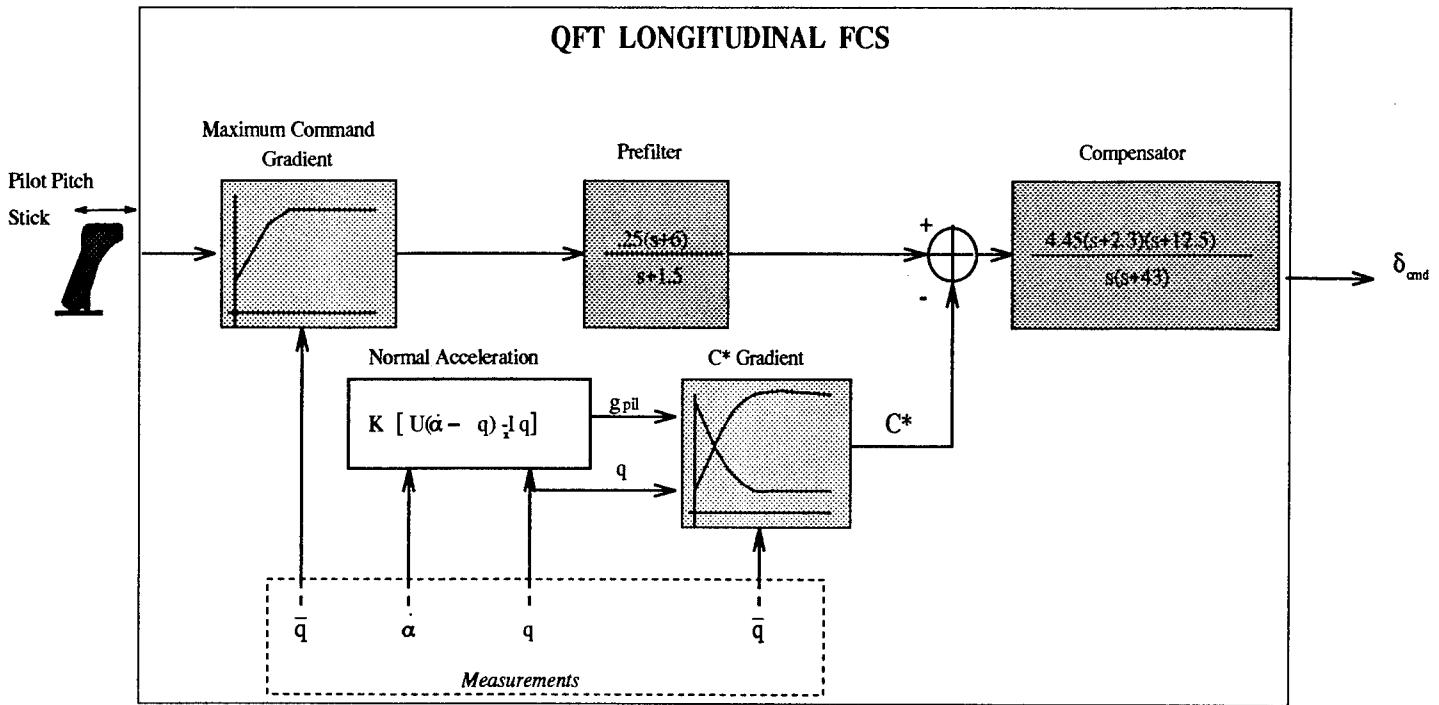


Figure 5.38 Final QFT Longitudinal FCS

first opportunity to determine the extent of control effector failures on the aircraft system. Though the templates expand both in magnitude and phase with increasing damage levels, the magnitude is most significantly impacted overall. From this analysis, the 25% failure level case is selected and the QFT bounds are generated. The tracking bounds reflect the template failure effects, expanding primarily in magnitude with respect to the healthy plants, while the external disturbance bounds present a unique problem and require some additional attention. With the composite bounds generated, the design advances to the loop shaping process. Though exceptionally restricted, a successful QFT compensator is formed and the design focus shifts towards performance evaluation. The initial unit step simulations and frequency domain validation with the exception of the external disturbance rejection prove to be quite encouraging. Finally, a maximum command gradient, as well as the rate and deflection saturation limitations are applied to the design and the results are evaluated. The final design appears as displayed in Fig. 5.38. A more complete evaluation of the design objectives and failure analysis follows in Chap. VII.

VI. Lateral/Directional FCS Design

This chapter covers the complete lateral/directional channel design process from the QFT feedback structure to the design of the compensators and specification validation.

6.1 Lateral/Directional Design

6.1.1 Lateral/Directional QFT Structure. Once again the first step in any QFT design is the formulation of the feedback structure. The general MIMO plant structure in Fig. 6.1 is repeated from Chap. III. Including a diagonal prefilter (**F**) and compensator (**G**), a dutch roll damper circuit and actuator dynamics the specific lateral/directional MIMO QFT structure can be found in Fig. 6.2. It is important to note that only the aileron and differential tail actuator dynamics are represented on Fig. 6.2. The rudder actuator, missing from this figure, is actually incorporated into the plant model through a dutch roll circuit. Furthermore, there are three inputs to the lateral/directional aircraft plant, yet there are only two feedback variables, roll rate p and sideslip β . Therefore, a 3X2 weighting matrix **W** is necessary to square the plant.

The incorporation of a dutch roll damper circuit (See Fig. 6.3) in the lateral/directional channel is a traditional method of eliminating the transient yaw rate resulting from an aileron deflection.[2] This circuit consists of feeding yaw rate r through a washout filter to command a counter rudder deflection. Yaw rate is selected as the control variable since it reflects an aircraft's dutch roll response, while the rudder is commanded because it primarily excites an aircraft's dutch roll mode. The purpose of the washout filter is to allow the pilot to command a steady-state yaw rate without causing an uncoordinated maneuver. The washout filter is simply a high-pass filter which, due to its position in the feedback path, enables the dutch roll damping circuit to remove (washout) a high frequency yaw rate response. The washout filter used in this design is found in Eq. (6.1).

$$H_{wash} = \frac{K\tau s}{1 + \tau s} \quad (6.1)$$

Selection of the feedback gain K and the washout filter time constant τ is highly dependent on the aircraft, its flight condition, and other plant parameters. For the VISTA F-16, both

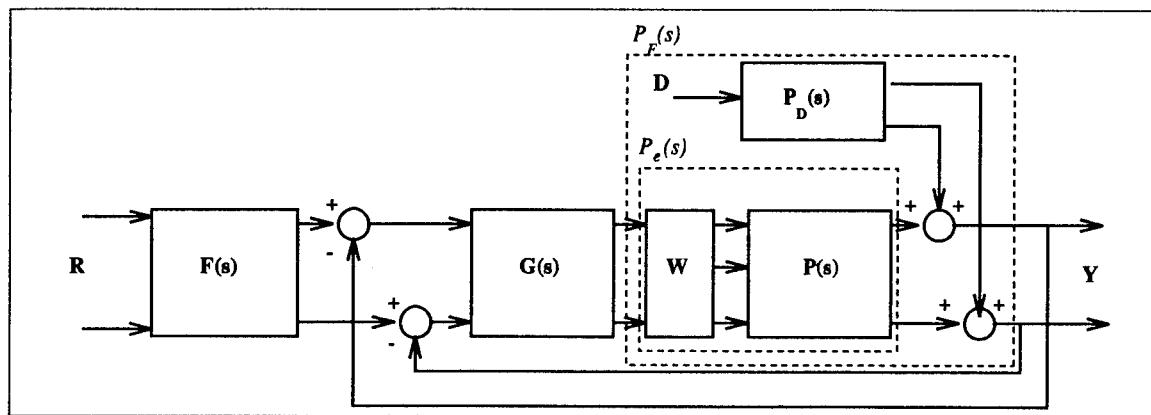


Figure 6.1 General MIMO QFT System with an External Disturbance Included

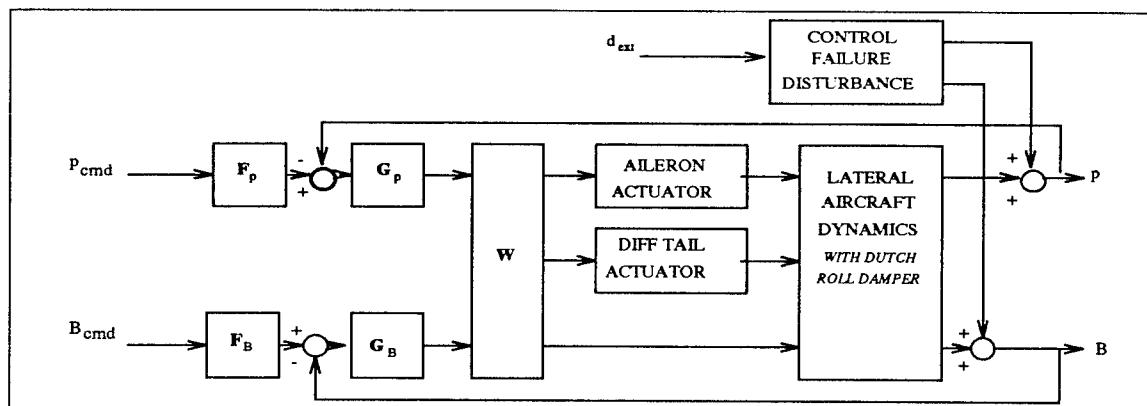


Figure 6.2 Lateral/Directional 2 X 2 MIMO System with an External Disturbance and Dutch Roll Damper

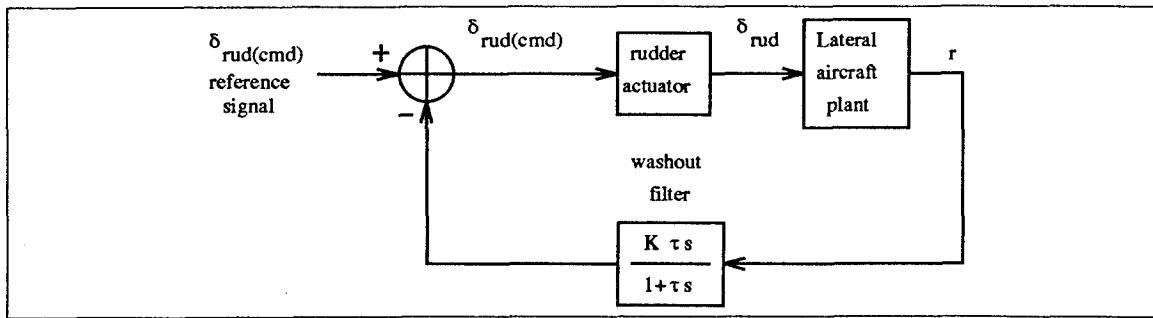


Figure 6.3 Dutch Roll Damper Structure

Reynolds [16] and Phillips [15] found that a $\tau = 3.33$ seconds maximizes dutch roll damping for the low \bar{q} flight condition, hence this value is selected in the current design. Choosing $\tau = 3.33$ seconds and $K = 1$, a root locus analysis is conducted on a range of plant cases to determine some robust gain for K that can be applied for the entire design set \mathcal{P} .

The first step in the root locus analysis is to select a subset of \mathcal{P} representative of the entire lateral/directional parameter space. Phillips found that the aircraft system differed most dramatically from one dynamic pressure extreme to the other, so a low and high \bar{q} flight condition was selected in his research. Since failure effects were not considered in previous VISTA research, the failures must be represented in the subset as well. Thus, yaw rate/rudder (r/δ_r) transfer functions are developed according to the procedure outlined in Chap. III for a low and high \bar{q} flight condition from each failure case in the design set. Given these transfer functions, a root locus is generated for each plant case. The root locus plots in Figs. 6.4, 6.5, and 6.6 are representative of the entire range of healthy and failed plants. It is evident from Figs. 6.5 and 6.6 that only the rudder failures effect the dutch roll mode, and the natural frequency of the dutch roll mode poles is reduced with rudder failure. The next step is to select a gain K to provide the maximum damping ratio for both the high and low \bar{q} plant cases. The '+' on the root locus plots represents the position of the closed loop poles for a gain = 1.4. Notice this gain only maximizes the high and low \bar{q} healthy aircraft damping (See Fig 6.4). As a compromise among the various plant sets, a unity gain is selected for the remainder of the design.

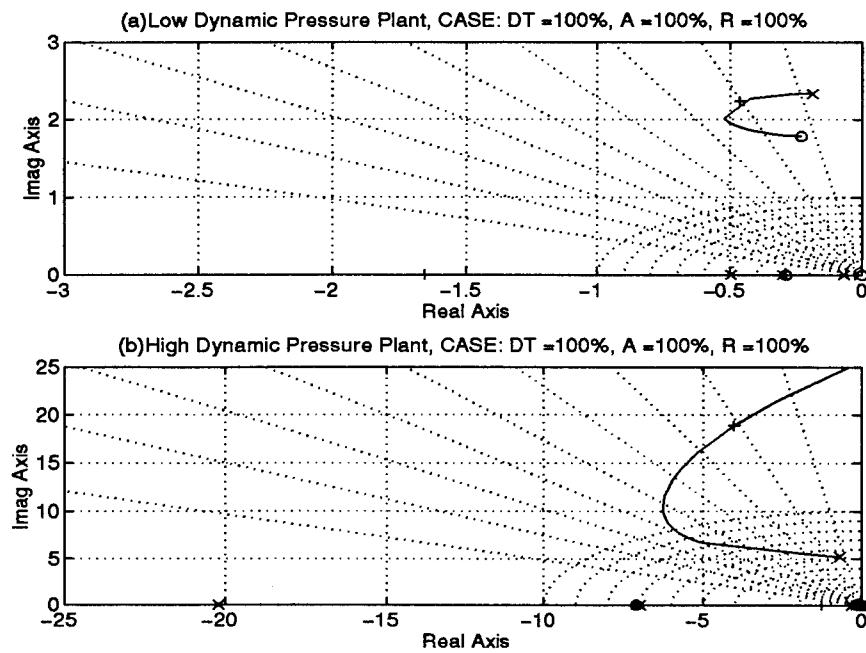


Figure 6.4 Root Locus Plots and Closed Loop Poles for Healthy Aircraft with Dutch Roll Damping Loop

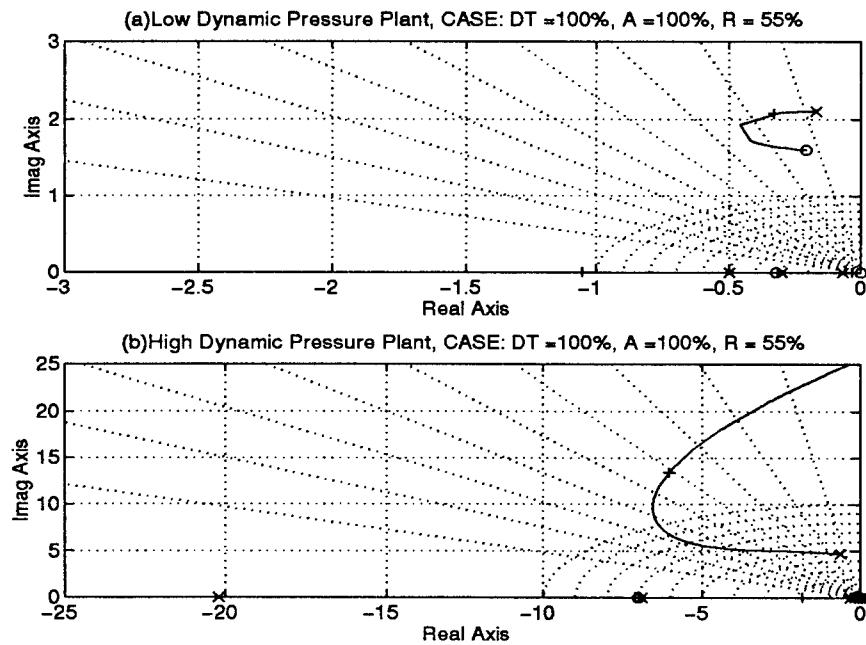


Figure 6.5 Root Locus Plots and Closed Loop Poles for 45% Rudder Failure with Dutch Roll Damping Loop

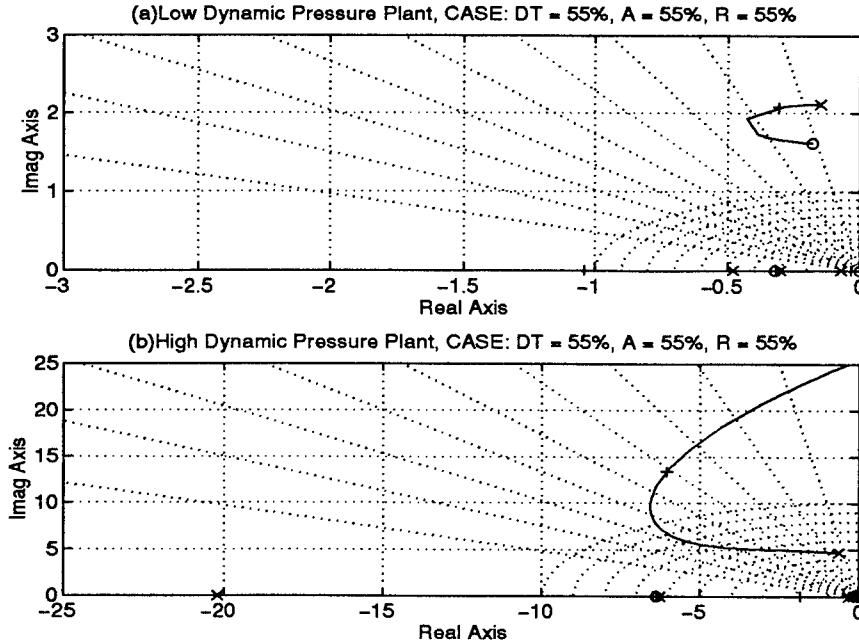


Figure 6.6 Root Locus Plots and Closed Loop Poles for 45% Stabilizer, 45% Aileron, and 45% Rudder Failures with Dutch Roll Damping Loop

6.1.1.1 Weighting Matrix. In this research the weighting matrix represents the distribution of roll command authority between the ailerons and the differential tail. Since the differential tail can only exhibit approximately a third of the aileron deflection, the selected weighting matrix (See Eq. (6.2)) reflects this limitation. Also, to achieve 'feet-on-the-floor' turn coordination an aileron/rudder interconnect is traditionally included in the weighting matrix. However, this interconnect is not included for a couple of reasons. First, Reynolds explored various weighting matrices in his attempt to construct a full subsonic envelope compensator for the VISTA, and he found that the aileron/rudder interconnect actually degrades the command response. From his research the aileron/rudder interconnect introduced a high frequency 'ringing' into both the roll-rate and sideslip output[16]. Second, there is an effective aileron/rudder interconnect already built into the MIMO QFT structure chosen for this design. By rejecting the cross-coupling disturbances each equivalent MISO case in the MIMO structure is effectively decoupled. Since the feedback variables are roll rate p and sideslip β , QFT decoupling translates into turn coordination.

| Class | LEVEL | | |
|----------|-------|-----|----|
| IV CAT A | 1 | 2 | 3 |
| | 1.0 | 1.4 | 10 |

Table 6.1 MILSTD 1797A Recommended Roll Mode Time Constants(seconds)

$$\begin{bmatrix} \delta_{dfail(cmd)} \\ \delta_{ail(cmd)} \\ \delta_{rud(ref)} \end{bmatrix} = W * \begin{bmatrix} p_{cmd} \\ \beta_{cmd} \end{bmatrix} = \begin{bmatrix} 0.294 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} p_{cmd} \\ \beta_{cmd} \end{bmatrix} \quad (6.2)$$

6.1.2 Lateral Specifications. In addition to the tracking, external disturbance, and stability performance specifications developed for the longitudinal channel, the cross-coupling specifications must also be defined for the lateral/directional design. All of these requirements are developed in the following sections.

6.1.2.1 Tracking Specifications. The majority of roll tracking specifications dictated by the MILSTD 1797A are in terms of time domain requirement such as minimum time to roll and maximum time to settle. The only specification that lends itself to frequency model generation is the roll mode time constants τ found in Table 6.1. Assuming the system settles within 4 time constants, the Level 1 specification can be interpreted as a 4 second settling time. Since the MILSTD does not directly specify a damping ratio ζ for the upper tracking bound T_{RU_p} , 0.5 is arbitrarily chosen. With this value of ζ and the Level 1 settling time specification, the two percent settling time formula

$$T_{settle} = \frac{4}{\zeta \omega_n} \quad (6.3)$$

found in Eq. (6.3) is used to identify $\omega_n = 2 \text{ rps}$ as the undamped natural frequency for the upper tracking bound. [5]

Given this value of natural frequency and a 0.5 damping ratio, Phillips placed a zero in the upper tracking model (Eq. (6.4)) to establish a 5 rps system bandwidth.

$$T_{RU_p} = \frac{4(s+1)}{s^2 + 2s + 4} \quad (6.4)$$

| Settling Times ¹ | | |
|-----------------------------|------|-------|
| Level | Spec | Model |
| 1 | 4 | 3.89 |
| 2 | 6.4 | 6.23 |
| 3 | 40 | 9.91 |

Table 6.2 Model settling times(seconds)

He also included an additional pole to the underdamped lower tracking bound, T_{RL1_p} , (Eq. 6.5). The purpose of this pole is to insure that the settling time does not exceed the 4 second limit for Level 1 roll tracking.

$$T_{RL1_p} = \frac{2.5}{(s + 1.25)(s + 2)} \quad (6.5)$$

Only the Level 2 and 3 lower tracking models require development in this design, since, like the longitudinal channel, the failed aircraft does not respond as quickly as the healthy aircraft. The Level 2 and 3 lower tracking models are developed following a similar modeling procedure established in Phillips' thesis. [15] The degraded roll mode time constants are transformed into settling time specifications and then the two percent settling time formula for a second-order model is applied. Additional poles are added to adjust the settling time of the system until it satisfies the MILSTD Level 2 and 3 time domain specifications. The models are found in Eqs. (6.6) and (6.7).

$$T_{RL2_p} = \frac{1.05}{(s + 0.75)(s + 1.4)} \quad (6.6)$$

$$T_{RL3_p} = \frac{0.375}{(s + 0.5)(s + 0.75)} \quad (6.7)$$

Finally, the frequency and step responses of the system are generated (Fig. 6.7) and the settling time data is gathered (See Table 6.2) to validate the tracking models.

The MILSTD does not impose boundaries on the β tracking response, since the pilot rarely attempts to track a sideslip angle except in refueling or terminal flight situations which are not considered in this design. Following Phillips' example, the upper and lower

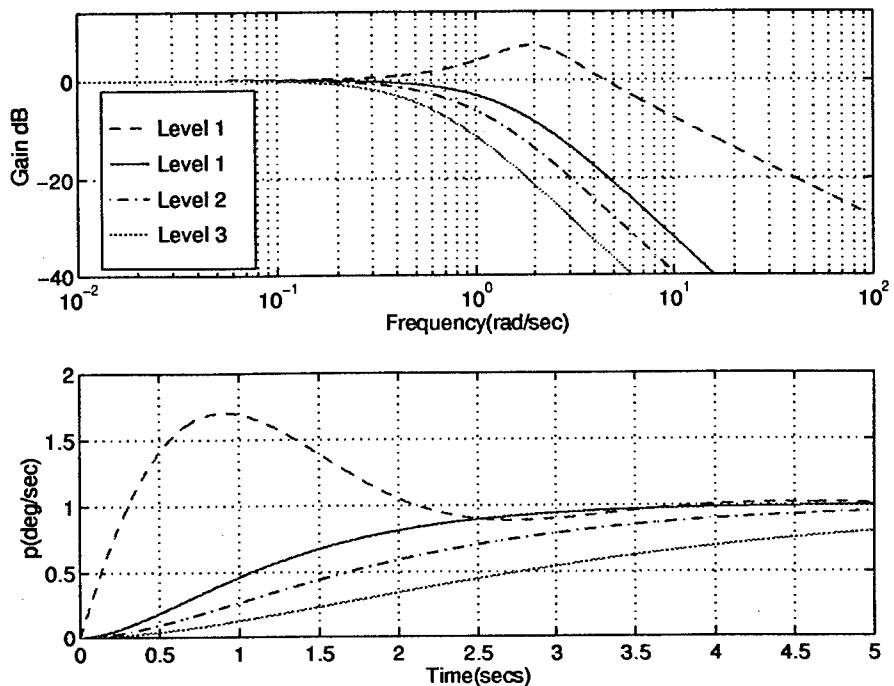


Figure 6.7 Roll Channel Level 1, 2 and 3 Tracking Specifications

boundaries (Eqs. (6.8) and (6.9)) are arbitrarily selected for the β response.

$$T_{RU_\beta} = \frac{4(s+1)}{s^2 + 2s + 4} \quad (6.8)$$

$$T_{RL_\beta} = \frac{1}{(s+1)^2} \quad (6.9)$$

6.1.2.2 Cross-coupling Specifications. The MILSTD does not provide a lucid and complete requirement for the development of QFT cross-coupling specifications. This ambiguity has lead previous designers to develop their own 'robust' specifications based upon either personal flight experience or time simulation analysis. From these developments two specific QFT cross-coupling specifications have been implemented. First, it is assumed that β is commanded so rarely that the coupling of β_{cmd} to p is not a major design consideration. If there is significant cross-coupling of the sideslip channel into the roll channel then this will appear during time simulations and corrected at that point in the design. The second cross-coupling specification places limitations on the β cross-coupling due to a p_{cmd} input. Unlike the $p/\beta cmd$ cross-coupling, $\beta/p cmd$ coupling is of

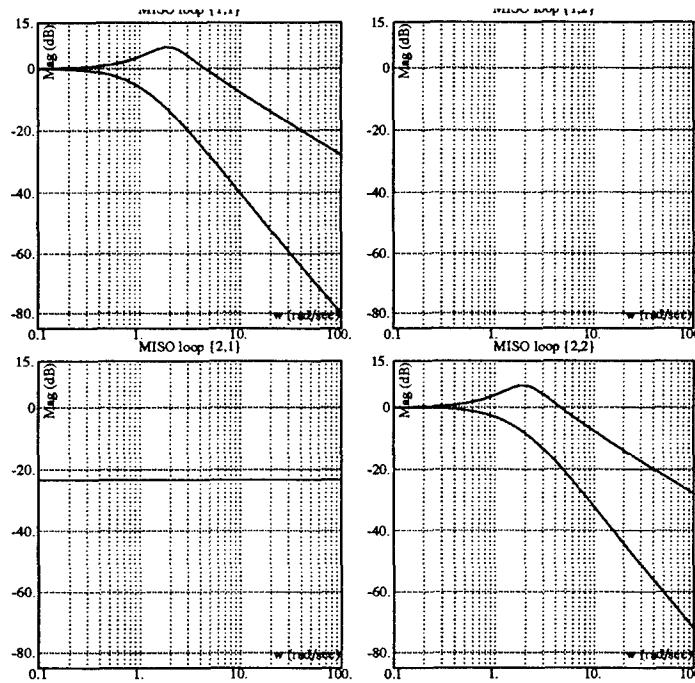


Figure 6.8 Lateral Channel Tracking and Cross-coupling Specifications

primary importance to a successful lateral/directional flight control system. To satisfy the β cross-coupling specifications, the aircraft must exhibit less than 0.067 degrees of sideslip for a unit step roll command at lower energy states (low \bar{q}) or 0.022 degrees of sideslip for a unit step roll command at higher energy states (high \bar{q}). Finally, there is also a 6 degree absolute maximum allowable sideslip limit levied on the maximum roll command input. The tracking and cross-coupling specifications are found in Fig. 6.8.

6.1.2.3 Stability Specifications. The same stability gain and phase margins employed in the longitudinal channel apply to the lateral/directional channel. Therefore the phase margin angle must be at least 30 degrees and the gain margin must be greater than 6 dB.

6.1.2.4 External Disturbance Rejection Specifications. Due primarily to the lessons learned in the longitudinal channel a -11 dB limit is arbitrarily placed on the systems external disturbance rejection response. However, like the longitudinal channel the external disturbance specifications are left to be validated in the time domain. Figure 6.9

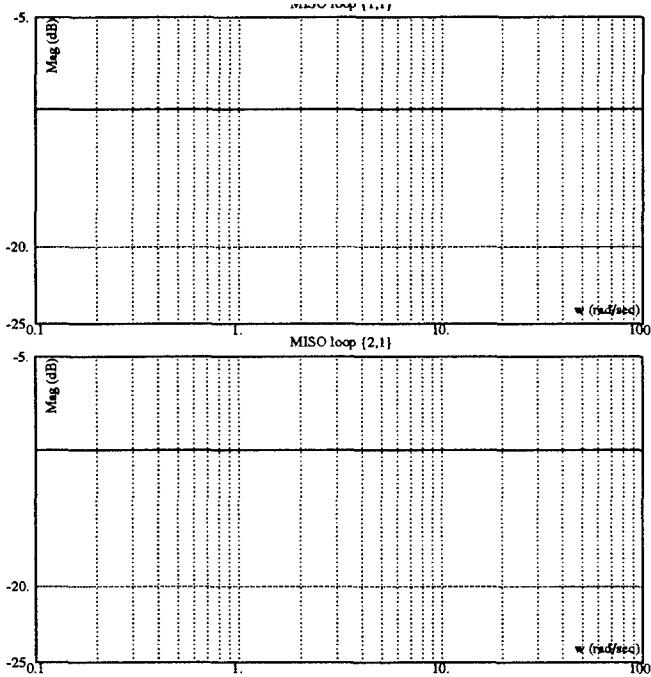


Figure 6.9 Lateral Channel Disturbance Rejection Specifications

displays the specification for both the roll (MISO loop(1,1)) and sideslip (MISO loop(2,2)) channels.

6.1.2.5 Performance Benchmarks. The performance specifications are dominated by the MILSTD roll angle requirements. These specifications like the cross-coupling requirements are not applicable to the entire subsonic envelope, instead they are dependent on the aircraft's forward velocity, U . This dependency is expressed in Table 6.3, where the speed range symbols are defined in Table 6.4.

| Level | Speed Range | 90 deg | 360 deg |
|-------|-------------|--------|---------|
| 1 | L | 1.4 | 4.1 |
| | M | 1.0 | 2.8 |
| 2 | L | | |
| | M | 1.3 | 3.4 |

Table 6.3 Roll Performance Specifications for MIL STD 1797A Class IV Aircraft

| Speed Range Symbol | Equivalent Airspeed Range |
|--------------------|---|
| L | $V_{min} + 20 \text{ KTS} \leq V < 1.4 V_{min}$ |
| M | $1.4 V_{min} \leq V < 0.7 V_{max}$ |

Table 6.4 Speed Range for MIL STD 1797A Class IV Aircraft

Level 3 handling qualities are excluded from consideration in the roll performance requirements (Table 6.3), since this level is reserved for especially disabled aircraft where stability is the only applicable specification.

6.1.3 Loaded and Effective Plants. With the 3 tank configuration plants eliminated from consideration in the longitudinal design it is pointless to include this configuration in the lateral/directional channel. The remaining 199 healthy plants are once again obtained from Phillips' data files in the form of state-space **A** and **B** matrices, and subjected to the failure modeling process detailed in Chap. IV. This failure modeling process in the lateral/directional channel is complicated by yet another factor, multiple control effectors. Now in addition to the plant parameter variation inherent in the healthy plants and the damage levels experienced in the longitudinal design, each plant can also experience single, double, or triple control failures. For each damage level selected, including the healthy case, there are eight possible failure combinations translating into 1592 failure plants.

A similar procedure to the one used in the longitudinal channel is applied to the selection of damage levels in the lateral/directional channel. From previous research it appears that the longitudinal channel due to its inherent instability is more sensitive to control effector failures than the lateral/directional channel. This difference in sensitivity is manifested in the increased level of failure imposed on the lateral/directional channel. Keating found that the URV with a 50% triple control effector failure could still maintain stability. However, he did not include in his analysis the limitations imposed by rate and deflection saturations that created some difficulties in successfully designing the longitudinal compensator. Considering these saturation limitations, a 45% damage level is selected with the 25% damage level as the backup plant set.

| | δ_{dt} | δ_a | δ_r | Disturbance |
|---------|---------------------|------------------|------------------|--------------|
| β | β/δ_{dt} | β/δ_a | β/δ_r | $\beta/dist$ |
| p | p/δ_{dt} | p/δ_a | p/δ_r | $p/dist$ |

Table 6.5 MIMO Plant Transfer Function Description

With the feedback structure defined in previous sections, and slightly greater than 3000 plants (1592 45% failed plants + 1592 25% failed plants) generated via the failure modeling process, a *Matlab* macro is employed to develop the associated QFT tracking and external disturbance transfer functions denoted in Table 6.5. The loaded plant matrix augmented with the dutch roll damper, discussed in Section 6.1.1, is 2X3 and the loaded disturbance plant matrix is 2x1. These plant matrices are formatted for input into *Mathematica* and consequently loaded into QFTCAD. The frequency responses for the 45% triple failure plant set and external disturbance plants are located in Figs. 6.10 and 6.11, respectively. The MISO loop(1,1) on Fig. 6.10 corresponds to the β/δ_{dt} transfer function found on Table 6.5, while MISO loop(2,3) on this figure corresponds to the p/δ_r transfer function. The other MISO loops correspond similarly to this table, including the disturbance transfer functions found in Fig. 6.11.

Ultimately, the weighting matrix described in Eq. (6.2) and the actuator dynamics found in Eq. (3.13) are placed in series with each loaded plant and the 2x2 effective plant matrix is generated via QFTCAD. The frequency response of these effective plant models can be found in Fig. 6.12, where the MISO loops correspond to the following variables:

- MISO loop (1,1) - β/β_{cmd}
- MISO loop (1,2) - β/p_{cmd}
- MISO loop (2,1) - p/β_{cmd}
- MISO loop (2,2) - p/p_{cmd}

6.1.3.1 Diagonal Dominance. The **Q** matrices are generated and the verification of the diagonal dominance condition (as $\omega \rightarrow \infty$)

$$|q_{11}(j\omega)q_{22}(j\omega)| > |q_{12}(j\omega)q_{21}(j\omega)| \quad (6.10)$$

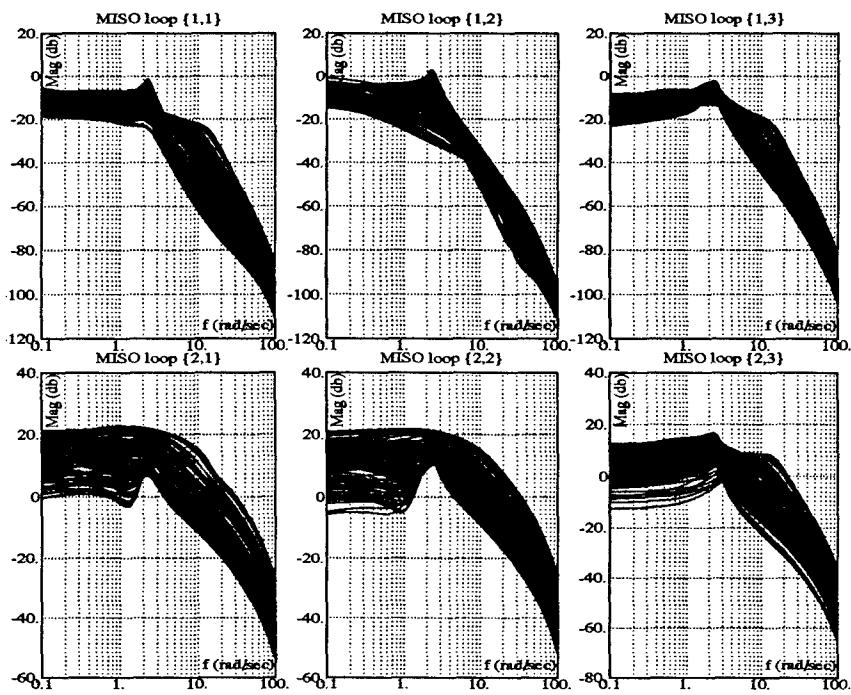


Figure 6.10 Frequency Response of Loaded Plant Models (P_L)

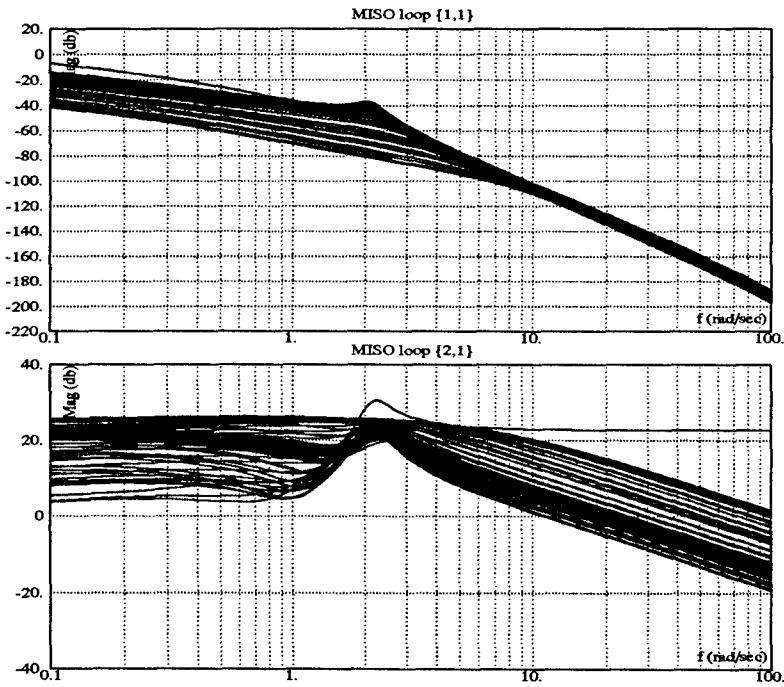


Figure 6.11 Frequency Response of External Disturbance Plant Models (P_D)

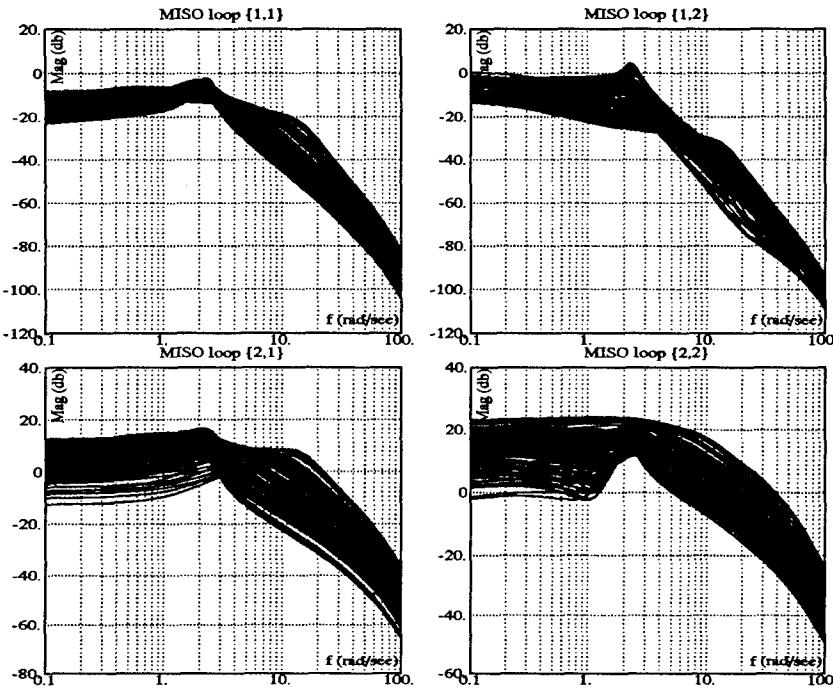


Figure 6.12 Frequency Response of Effective Plant Models (P_e)

is readily determined by QFTCAD. The diagonal dominance plot is found in Fig. 6.13. Though the responses are negative over a large portion of the bandwidth, the condition is satisfied as ω approaches infinity. With diagonal dominance a Method 1 MIMO QFT design can be accomplished as previously discussed in Chap. II.

6.1.4 Frequency templates. After the plant cases and external disturbance plants are loaded, and manipulated to form the \mathbf{P} , \mathbf{P}_e , \mathbf{P}_D , and \mathbf{Q} matrices the QFTCAD 'Temp' option automatically generates the frequency templates for each of the two lateral/directional channels. These β and p templates are developed over the same range of frequencies (See Eq. (5.7)) utilized in the longitudinal design.

6.1.4.1 Healthy Aircraft Templates. Phillips' templates are used to benchmark the healthy aircraft models developed in this research. This comparison of healthy plant templates serves as an important milestone in the research. If the templates match, then it assures that the several *Matlab* routines employed to generate the models are working correctly, and that there is sufficient reason to assume the failure templates are correct

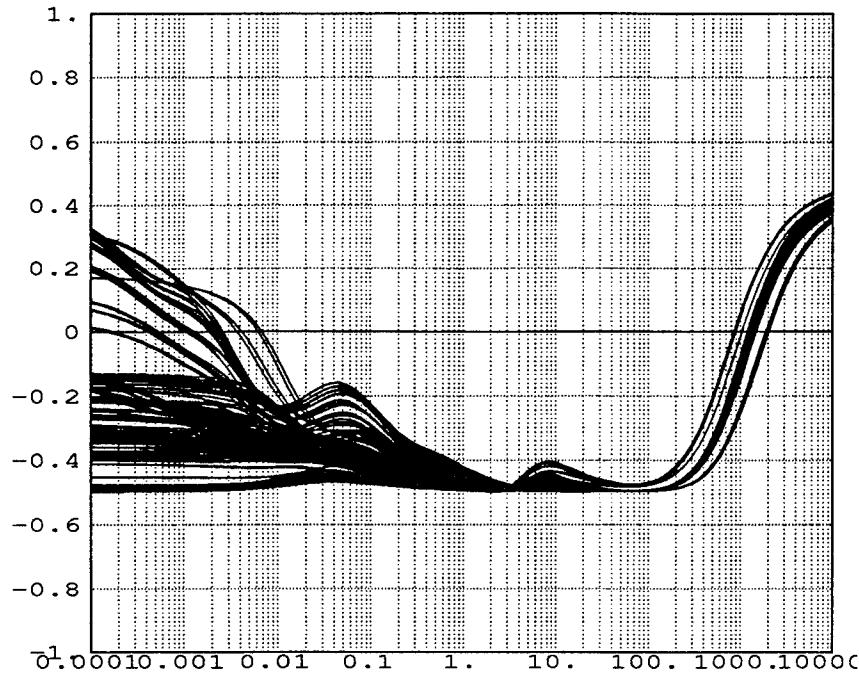


Figure 6.13 Diagonal Dominance Validation

as well. Fortunately, in the lateral/directional channel the healthy plant models from the previous design match identically with those generated in this design. Unlike the longitudinal channel, Matlab's *linmod* function provided the identical transfer functions as those developed by closing the dutch roll damper via matrix manipulation. The discrepancy found in the longitudinal channel appears to be caused by the non linear weighting scheme in the simulation diagram, and is discussed further in Appendix E.

The healthy plant frequency templates for the β and p channels can be found in Figs. 6.14 and 6.15. These figures provide a basis of comparison for the failed templates which are discussed in the following section.

6.1.4.2 Failed Aircraft Templates. The single failure templates are displayed in Figs. 6.16 through 6.23. To aid in the comparison of healthy versus failed plant cases, the healthy plant templates are superimposed on the failure templates. These figures convey considerable information about the effects of failures on the aircraft. First, each control surface failure effects the related aircraft mode. For example, a 45% aileron failure has little effect on the β templates found in Fig. 6.16, while resulting in a 5 dB expansion

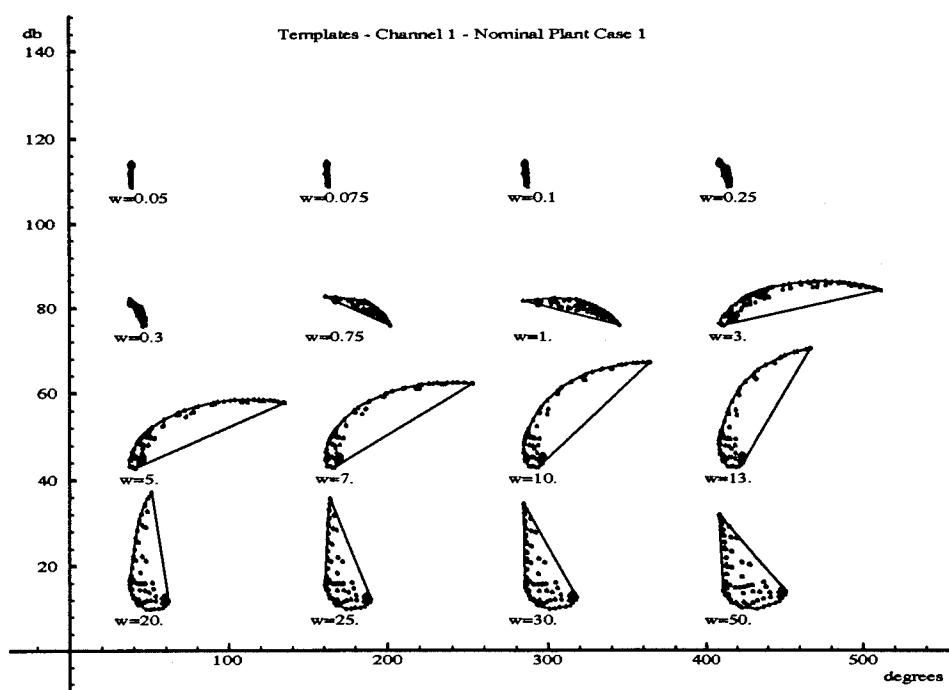


Figure 6.14 Healthy Aircraft, Beta Templates

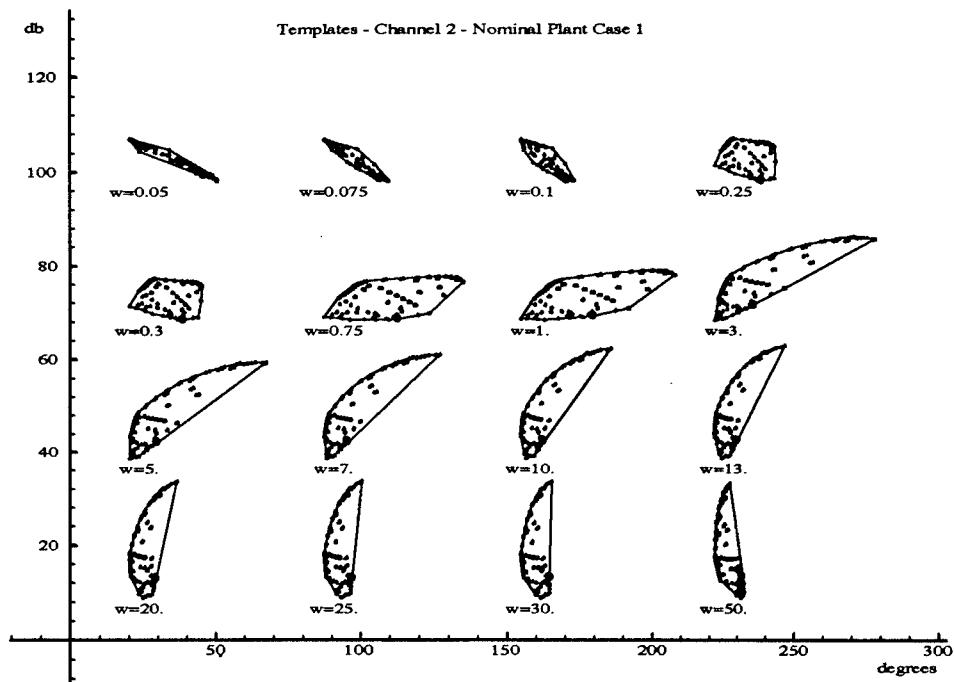


Figure 6.15 Healthy Aircraft, Roll Templates

of the p templates found in Fig. 6.17 and enlarged in Fig. 6.18. Similarly, a 45% rudder failure displays a 5 dB expansion of the β templates in Fig. 6.19 and Fig. 6.20, but has little effect on the p templates in Fig. 6.21. This isolation of failure effects agrees with the relationships developed in Chap. IV, and the physical laws governing the aircraft's failure response.

In addition to failure isolation, the failed templates exhibit another curious relationship. Like the longitudinal failure templates, the lateral/directional templates increase primarily in magnitude. It appears from the analysis of Figs 6.16 through 6.23, that the control derivatives, which have the greatest impact on the system gain, are most effected by the control effector failures. Though this finding seems to justify modifying only the state-space **B** matrix in control effector failure analysis, the compensator design proves otherwise.

Finally, since $C_{l_{PF}}$ is the only stability derivative involving multiple control effector failures in its formulation, the multiple failure cases are simply composites of the worst case single failure templates (largest magnitude and phase template cases) identified in the single failure analysis (See Figs. 6.24 and 6.25). These composite failure plant sets justify the use of only the 199 triple failure cases to adequately represent the entire failed parameter space. If a clear relationship between multiple control effector failures and template growth could not be established, then a list of plants lying on the perimeter of each failure case, for each frequency, would have to be assembled. Fortunately, the 45% triple failure case is applied as the basic plant set for the remainder of the lateral/directional design. If a successful QFT design can not be accomplished for the 45% triple failure template design, then the backup 25% triple failure set will be implemented.

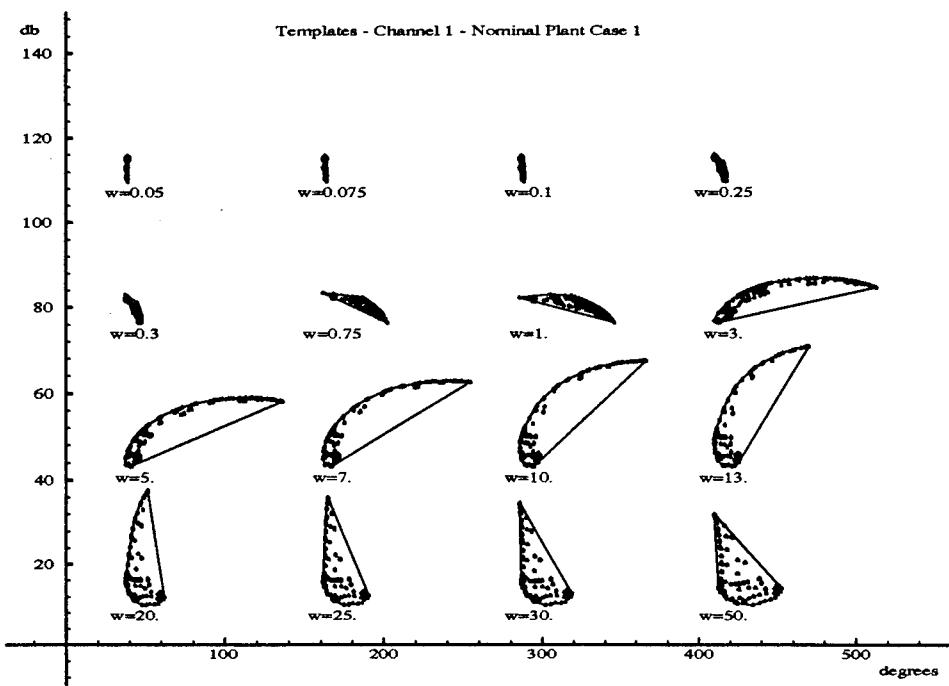


Figure 6.16 45% Aileron Failure, Beta (β) Templates

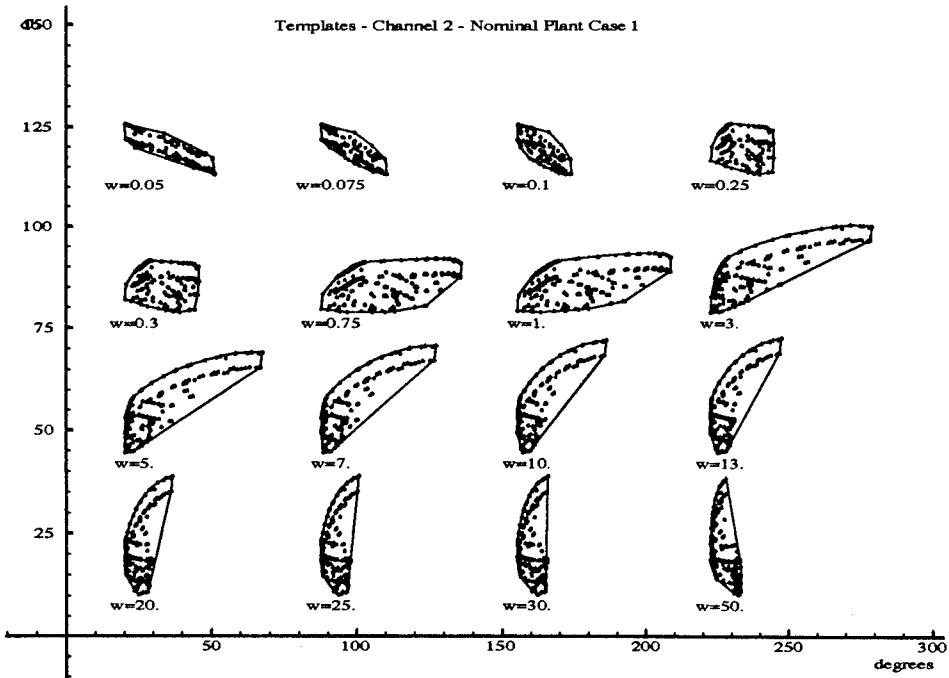


Figure 6.17 45% Aileron Failure, Roll (p) Templates

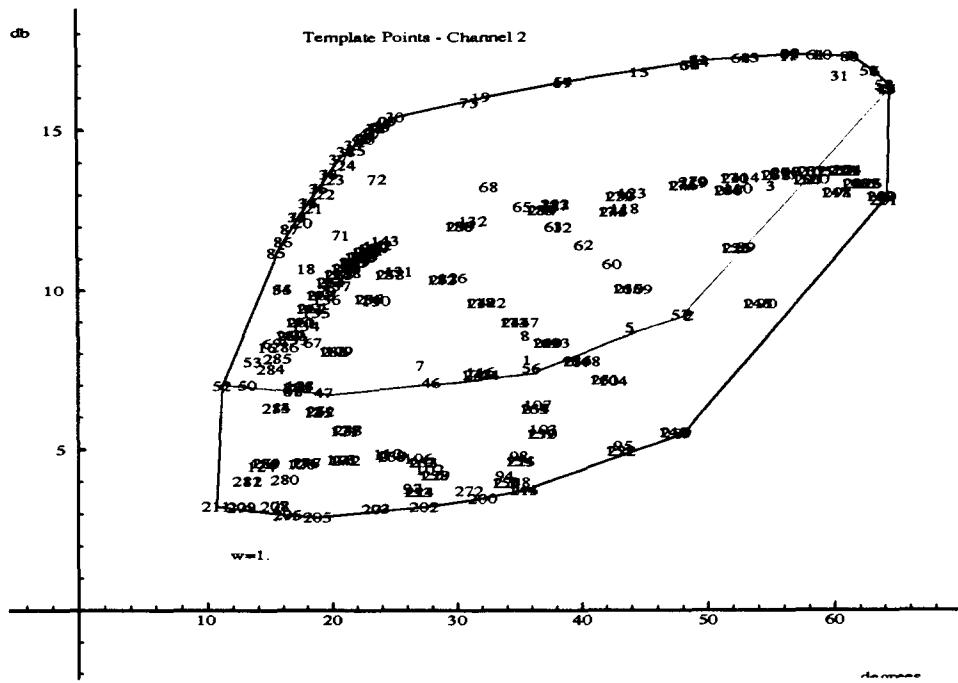


Figure 6.18 45% Aileron Failure, Roll (p) Template for $\omega = 1$ rps

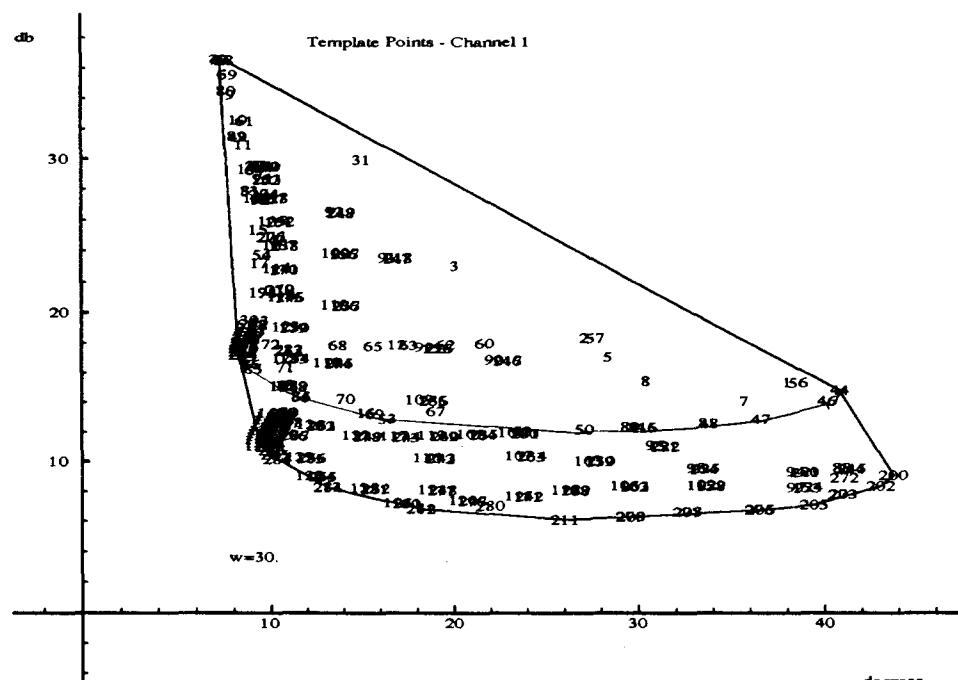


Figure 6.19 45% Rudder Failure, Beta (β) Template for $\omega = 30$ rps

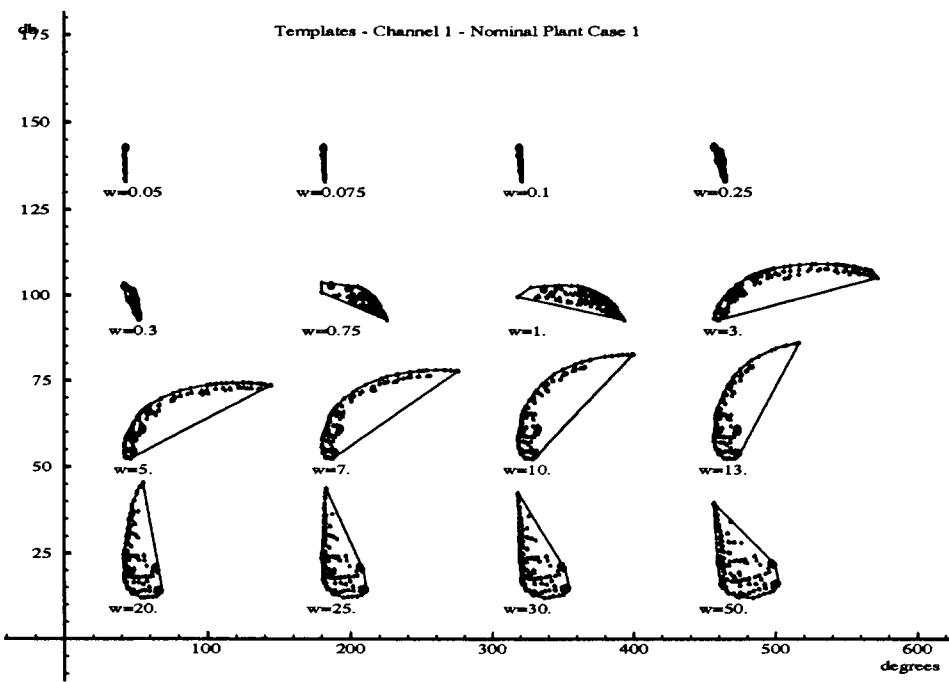


Figure 6.20 45% Rudder Failure, Beta (β) Templates

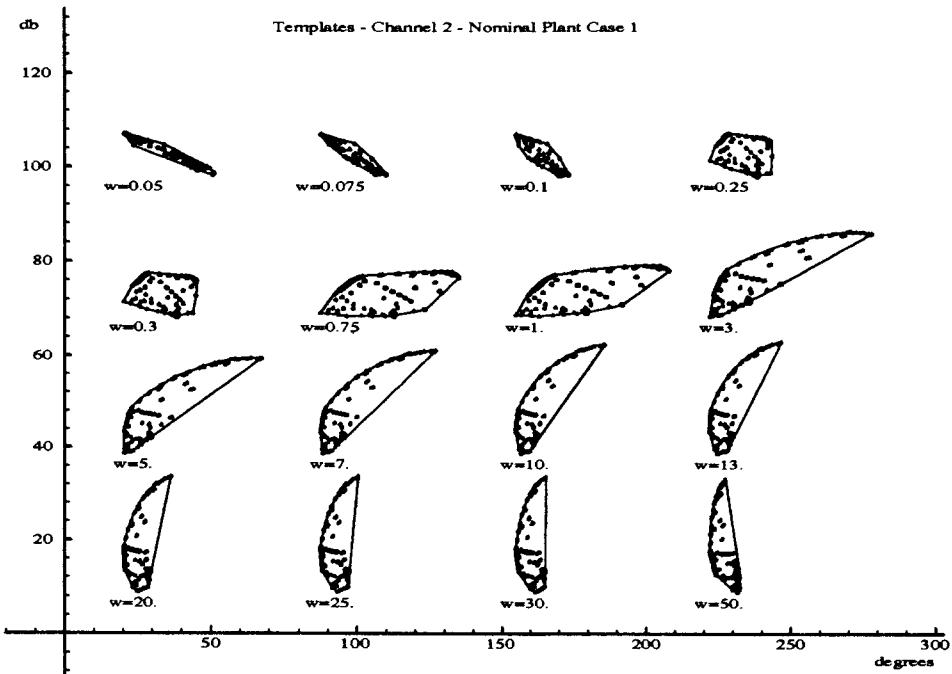


Figure 6.21 45% Rudder Failure, Roll (p) Templates

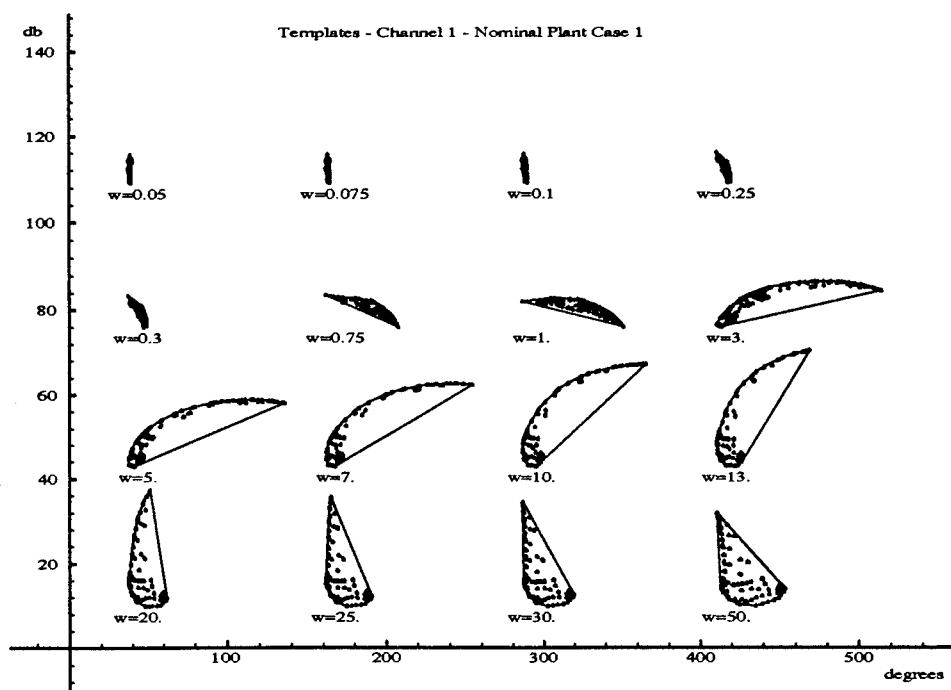


Figure 6.22 45% Differential Stabilator Failure, Beta (β) Templates

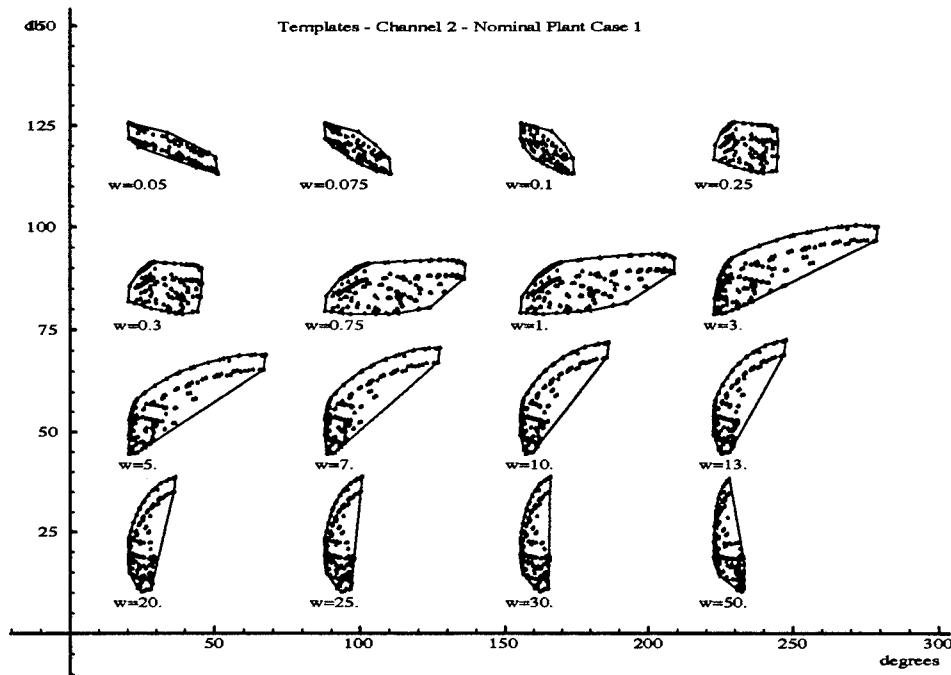


Figure 6.23 45% Differential Stabilator Failure, Roll (p) Templates

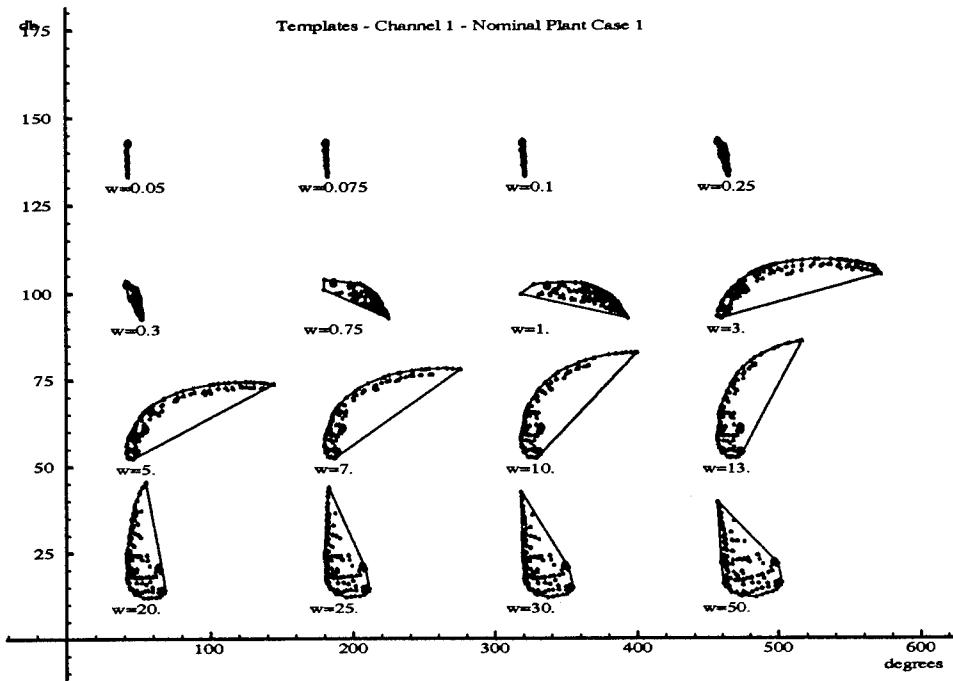


Figure 6.24 45% Triple Failure, Beta (β) Templates

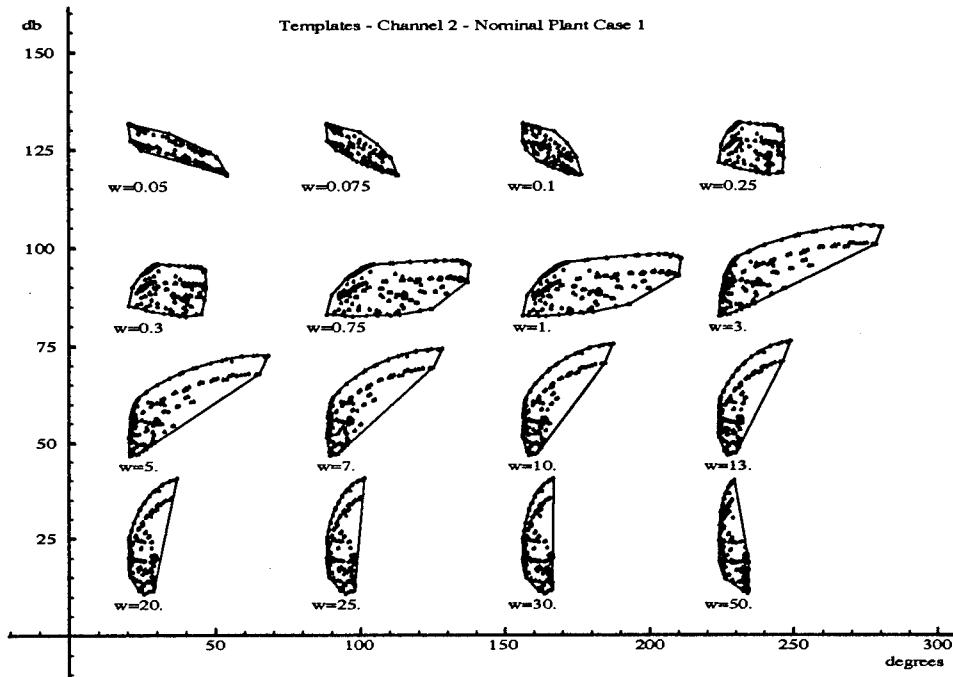


Figure 6.25 45% Triple Failure, Roll (p) Templates

6.1.5 QFT Generated Bounds. The nominal plants for both the roll and beta channels are selected on top of the 30 rps frequency templates. The nominal plant for the roll channel is SRF plant #4, corresponding to the 50,000 ft Mach 0.9 trim condition, and the nominal plant for the beta channel is SRF plant #89, corresponding to the 10,000 ft Mach 0.85 trim condition. With these nominal plants, as well as the **Q** matrices and all QFT tracking and disturbance models previously identified, the QFT bounds for tracking, cross-coupling, stability, and external disturbance are formed.

6.1.5.1 Tracking and Stability Bounds. The low frequency roll tracking bounds in the range of 0.05 to 0.1 rps are extremely restrictive requiring a gain increase in excess of 45 dB, however the boundaries in the bandwidth of the pilot are achievable with significantly less gain. Therefore, the lower frequency bounds are selectively disregarded and the focus is concentrated on satisfying the bounds within the pilots bandwidth. Fortunately, as previously mentioned, Phillips' lateral/directional models match identically to the healthy models developed in this research. These healthy models (See Figs. 6.26 and 6.28) provide yet another opportunity to evaluate failure effects on the system's tracking response. It is anticipated that the tracking bounds are more restrictive for the failure case, since more control effector authority is required to perform a particular tracking task. This expectation is confirmed in evaluation of Figs. 6.26 and 6.27, where the failed tracking bounds are approximately 5 dB greater than the healthy bounds at 0.75 rps. These more restrictive tracking bounds are the result of the taller(increased gain) failure templates. Finally, though the failed stability bounds demonstrate an increase in gain commensurate with the damage level there is not an appreciable difference in phase between the healthy and failed cases.

The sideslip (β) channel tracking and stability bounds show similar effects to the roll channel bounds. The failed aircraft boundaries shown in Fig. 6.29 are approximately 7 dB greater then the healthy bounds at 0.75 rps. These enlarged boundaries are once again the result of the failed aircraft's taller stability bounds. These stability bounds are unlike the roll channel stability bounds, since they show both an increase in magnitude and phase when compared to the healthy boundaries found in Fig. 6.28. This increase in phase can

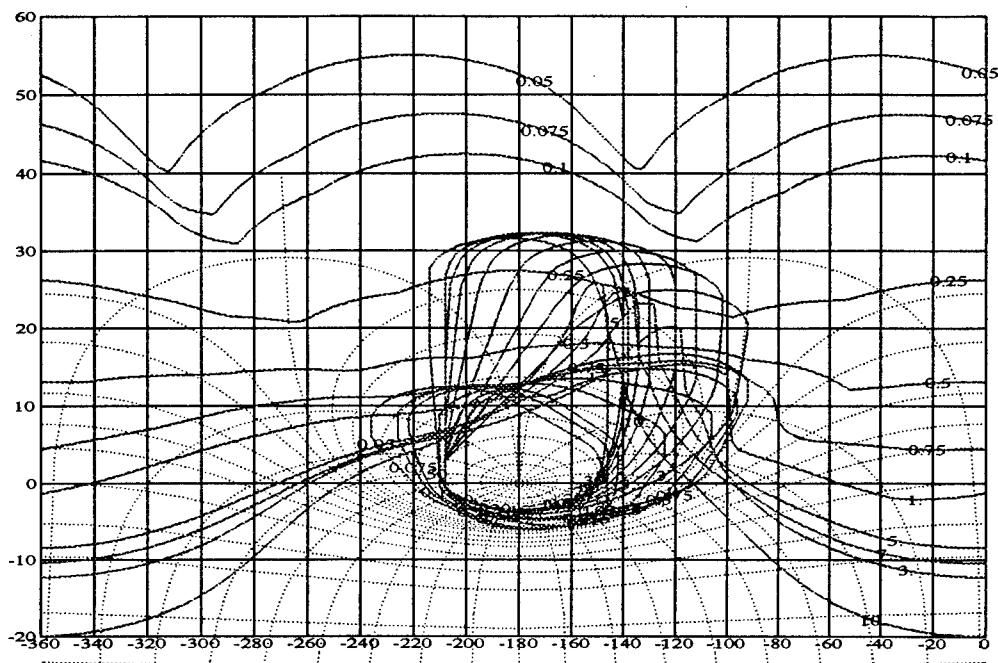


Figure 6.26 QFTCAD Stability and Tracking Bounds for the Roll Channel of the Healthy VISTA F-16

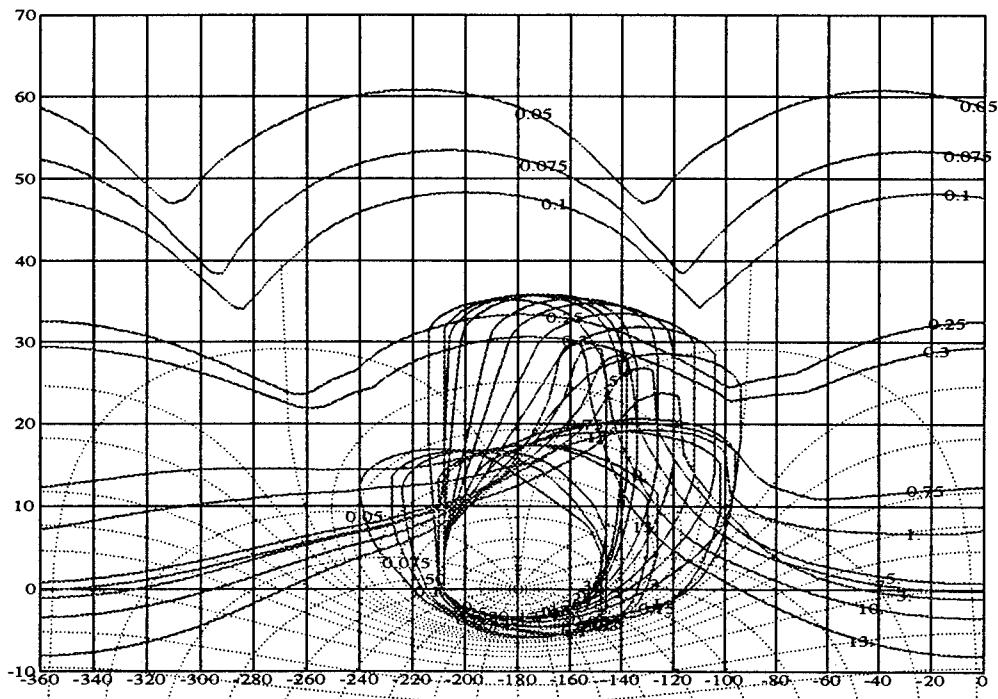


Figure 6.27 QFTCAD Stability and Tracking Bounds for the Roll Channel of VISTA F-16 Experiencing a 45% Triple Failure

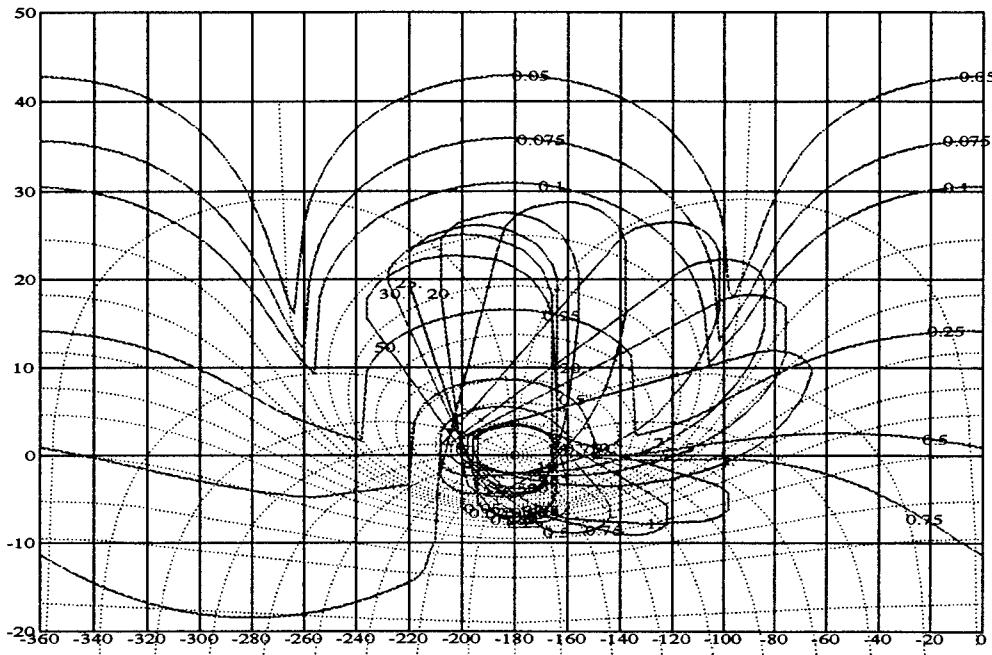


Figure 6.28 QFTCAD Stability and Tracking Bounds for the Beta Channel of the Healthy VISTA F-16

be traced to the failure modeling discussed in Chap. IV. The roll channel failures have the greatest impact on the control derivatives of the system, while the beta channel failures have an appreciable effect on both the stability and control derivatives.

6.1.5.2 External Disturbance Bounds. The external disturbance bounds (See Figs. 6.30 and 6.31) for both the roll and beta channels are both too restrictive to achieve. These bounds are selectively removed from the composite boundary and time simulations are evaluated to determine whether the responses require additional disturbance rejection.

6.1.6 Compensator Design. The same constraints identified in Chap. II apply to the lateral/directional design as well. Fortunately, the lateral/directional channel is inherently stable reducing the restrictions encountered in the longitudinal FCS design. The development of the roll p and sideslip β compensators follows.

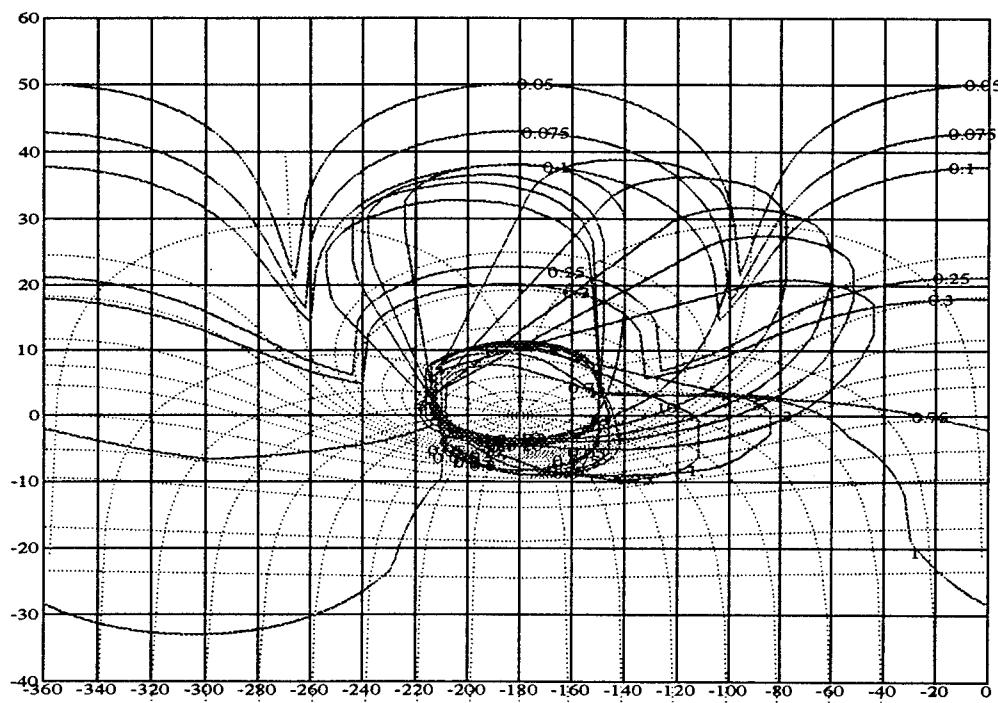


Figure 6.29 QFTCAD Stability and Tracking Bounds for the Beta Channel of the VISTA F-16 Experiencing a 45% Triple Failure

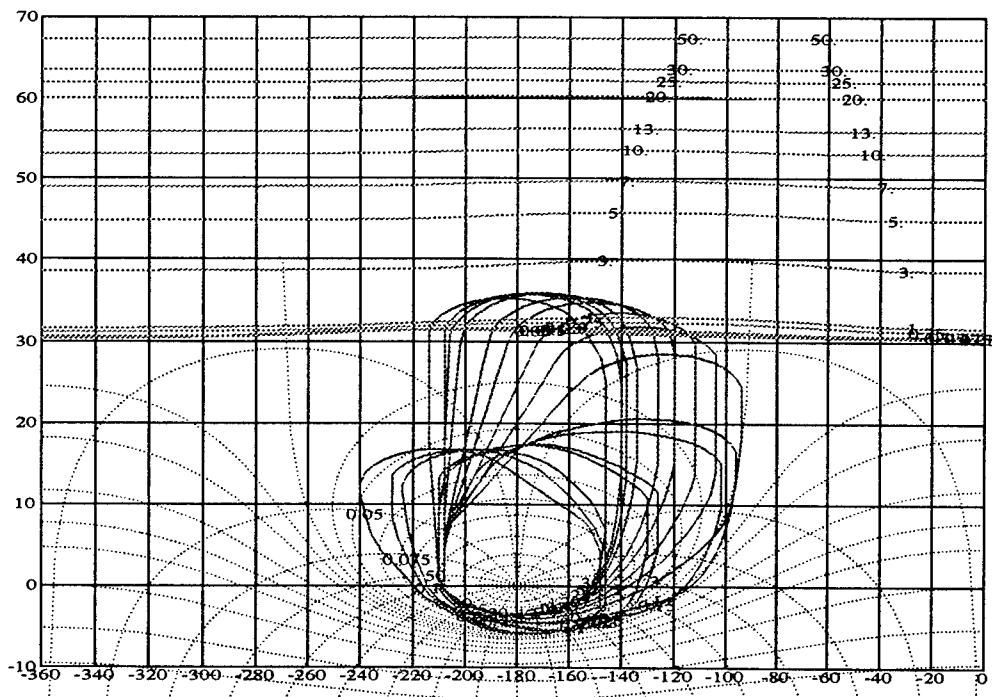


Figure 6.30 QFT External Disturbance Bounds for Roll Channel

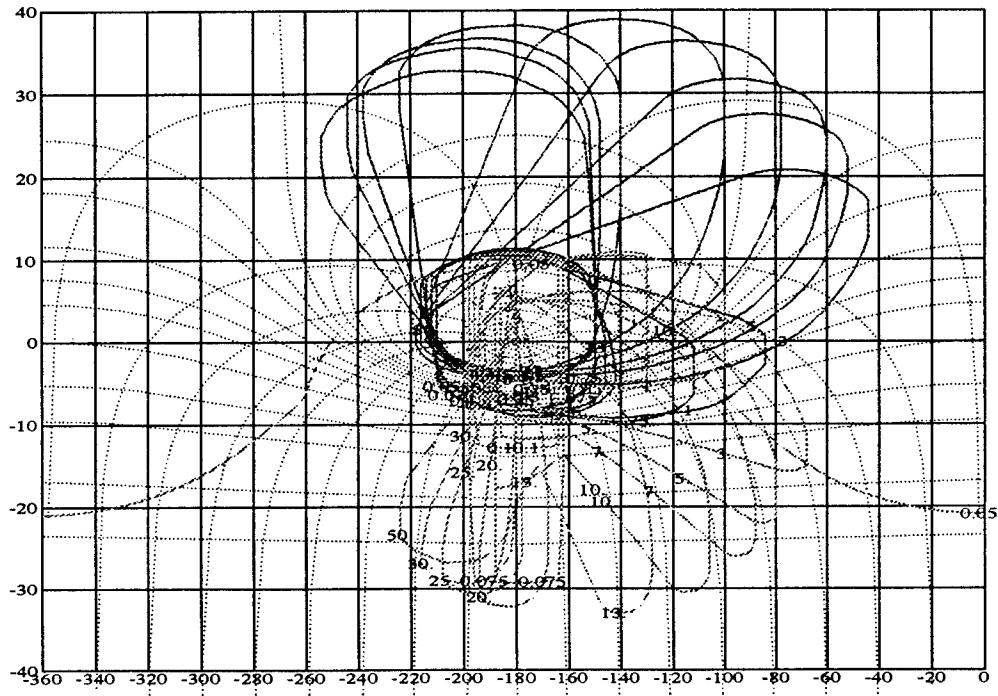


Figure 6.31 QFT External Disturbances Bounds for Beta Channel

6.1.6.1 Roll Channel. One of the goals of this fault tolerant control law enumerated in Chap. II is to generate a system that can maintain nominal performance without control effector failures and maintain stability with failures. Since Phillips's compensator already guarantees that the former condition is satisfied then if the design can be manipulated only enough to provide stability and Level 3 tracking response for the failed plants, then the specified design criteria will be satisfied. Thus, as a starting point, Phillips' compensator is loaded and evaluated.

Since the major contribution of the control effector failures is to increase the gain required to achieve a particular level of tracking response, it is assumed that Phillips' compensator would require some additional gain. However his compensator nearly met all tracking and stability bounds due to some inherent overdesign in his compensator. Only the lower \bar{q} plants of the failed plant set violated the associated stability bounds. To satisfy these exceptional plants, the roll compensator zero is adjusted from 3.5 rps to 4 rps. The final roll compensator G_p is found in Eq. (6.11), and on Fig. 6.32.

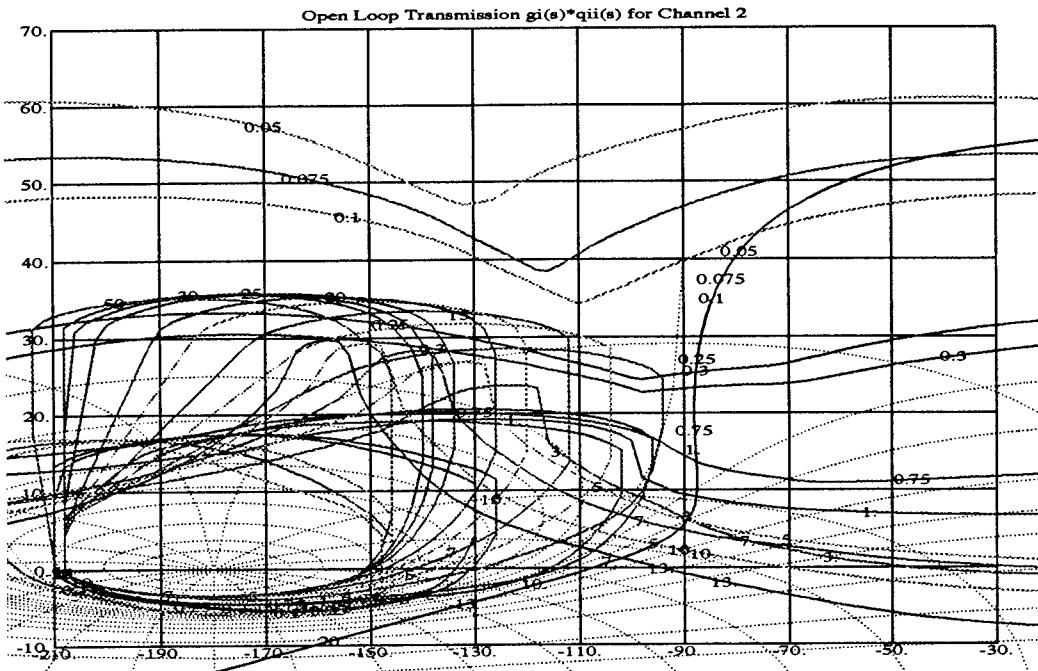


Figure 6.32 QFTCAD Tracking Bounds and Nominal Loop for Roll Channel with 45% Triple Failure

$$G_p = \frac{0.10(s + 4)}{s} \quad (6.11)$$

6.1.6.2 Sideslip Channel. In an effort to reduce the design restrictions on the beta compensator only satisfaction of the stability bounds is attempted. Following a similar line of reasoning established in the roll compensator design, Phillips' compensator is initially loaded and evaluated in this design.

Once again his compensator nearly satisfies all the stability requirements for the failed plant as well as the healthy plant set. However, it is apparent from initial roll response simulations that the sideslip angle cross-coupling does not meet specifications, and that gain scheduling must be utilized in order to achieve the desired cross-coupling. As in Phillips' design, $150 \text{ lbs}/\text{ft}^2$ appears to be a natural division among the plants cases identified on the sideslip frequency templates. Therefore the gain for $\bar{q} \leq 150 \text{ lbs}/\text{ft}^2$ is adjusted to 60 and for $\bar{q} > 150 \text{ lbs}/\text{ft}^2$ it is set at 110. The increase in the low \bar{q} gain however causes some of these plants to violated the QFT stability bounds. As a

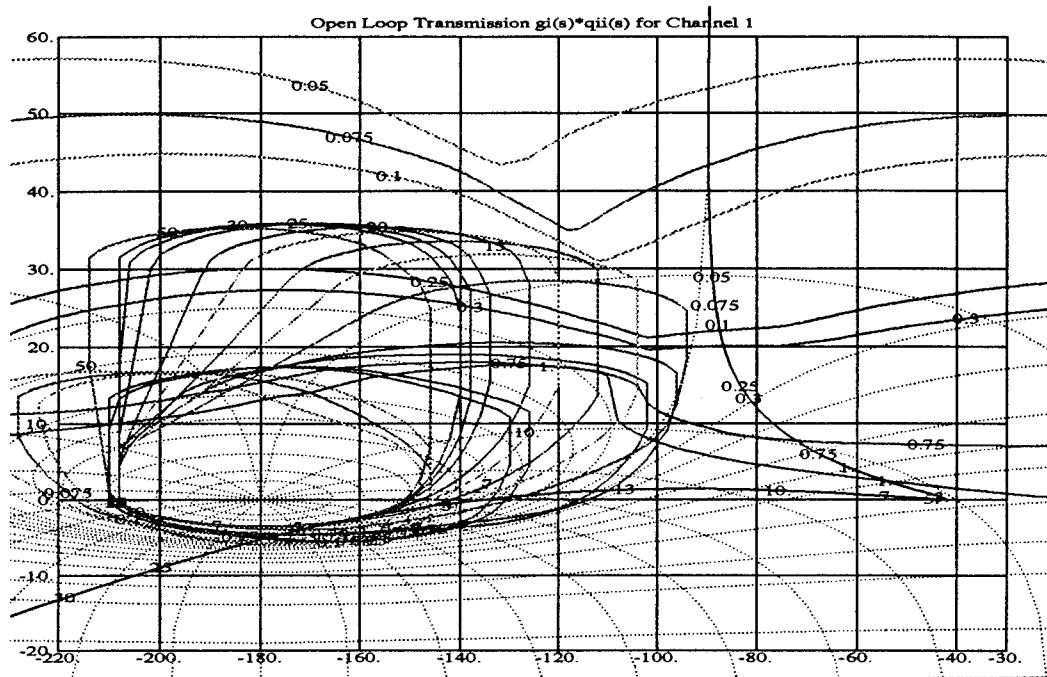


Figure 6.33 QFTCAD Tracking Bounds and Nominal Loop for Beta Channel with 45% Triple Failure

final adjustment the zero at 1.7 rps is shifted lower in frequency to 1.35 rps providing additional increase in phase necessary to circumvent the lower frequency stability bounds. The nominal loop in Fig. 6.33 clearly satisfies all of the stability bounds and the tracking bounds within the higher frequency range of the pilots bandwidth. The final compensator is listed in Eq. (6.12).

$$G_\beta = \frac{K_\beta(s + 1.35)(s + 2)}{s(s + 60)} \quad (6.12)$$

where $K_\beta = -60$ for $\bar{q} \leq 150 \text{ lbs}/\text{ft}^2$ and $K_\beta = -110$ for $\bar{q} > 150 \text{ lbs}/\text{ft}^2$

6.1.7 Prefilter Design. The final component necessary to successfully complete the QFT design process is the prefilter \mathbf{F} . The purpose of the prefilter is especially important in this MIMO FCS design, for a properly designed prefilter can insure the desired tracking response as well as reduce the inherent cross-coupling between the two channels. The roll channel prefilter is designed first and the beta channel prefilter thereafter.

6.1.7.1 Roll Channel. A pole is introduced to limit the system response within the pilot's bandwidth, however it is apparent that a zero is necessary to position the tracking response within the Level 3 tracking bounds. The dutch roll damper has a deleterious effect on the low frequency tracking response of the low \bar{q} plants. It appears that the dutch roll damper slows the roll responses within this frequency range creating a droop in the tracking response. The introduction of a second pole is then warranted to mitigate the effects of this zero on the higher frequency tracking response. The prefilter found in Eq. (6.13) guarantees that the Level 1, 2 and 3 roll tracking specifications are satisfied.

$$F_p = \frac{7.58(s+2)}{(s+1.1)(s+15)} \quad (6.13)$$

6.1.7.2 Sideslip Channel. The removal of the beta tracking bounds from consideration in the sideslip channel design appears to obviate the need for a sideslip channel prefilter. Though beta tracking is not a primary design objective, the nominal loop in Fig. 6.33 clearly shows that the system has the robustness required to track a β_{cmd} within the desired specifications. Consequently, the first prefilter design is employed to position the beta tracking responses within the tracking boundaries. However after some preliminary tracking validation plots, a curious relationship became apparent. The cross-coupling of the roll response to a β_{cmd} input became more severe as the prefilter is adjusted to fit within the tracking bounds. In light of this relationship and the fact that the beta tracking models are arbitrarily generated, the compensator in Eq. (6.14) is applied to achieve the best beta tracking response while minimizing the effect of roll on the beta cross-coupling.

$$F_\beta = \frac{3.5}{(s+3.5)} \quad (6.14)$$

6.2 Time Simulations

The purpose of the time simulations is to determine if the compensated system satisfies the time domain specifications. In addition to verifying specifications, the simulation data is employed to construct a maximum command gradient for both roll and sideslip channels.

6.2.1 Tracking. Similar to the longitudinal design (page 5-20) a sample of 20 tracking responses is presented over a specified \bar{q} region, where the solid lines represent the healthy aircraft and the dashed lines represent the failed aircraft responses.

6.2.1.1 Roll Tracking Responses. Dynamic pressure \bar{q} has the most significant impact among all other plant parameters including control effector failures. The low \bar{q} time responses in Figs. 6.34, 6.35, and 6.36 clearly represent the worst case design scenarios. The low \bar{q} responses exhibit the greatest roll p settling times, the worst beta β cross-coupling, and a noticeable increase in control surface deflection. Yet despite their inherent shortcomings these responses satisfy the primary lateral design criteria. The simulations demonstrate that all healthy aircraft responses meet Level 1 tracking specifications, the failed aircraft responses are within Level 1 or Level 2 tracking specifications, and the beta cross-coupling response (See Fig. 6.35) does not exceed the 0.067 limit for low \bar{q} plants. The low \bar{q} time responses also demonstrate the domination of the available control authority by the failed plants. The consequences of this domination become a factor later in the design when the rate and deflection saturation nonlinearities are applied.

The high \bar{q} time responses illustrated in Figs. 6.37, 6.38, and 6.39 show a dramatic improvement in overall performance when compared to the low \bar{q} plants. All the plants, healthy as well as those experiencing 45% triple failure, meet or exceed Level 1 roll tracking specifications. The high \bar{q} plants exhibit significant robustness especially evident in the roll angle ϕ and sideslip angle β responses. The gain scheduling introduced to satisfy the 0.067 sideslip angle limit for the low \bar{q} plants enabled the design to achieve the more restrictive 0.022 sideslip limit for the high \bar{q} cases as well. The satisfaction of the sideslip angle requirements is found on Fig. 6.38, and in the complete tabular listing of all lateral time responses in Appendix D.

6.2.1.2 Sideslip Tracking Responses. The unit sideslip step responses in Figs. 6.40, 6.41, and 6.42 reflect the design emphasis placed on roll performance and turn coordination over sideslip tracking. In other words, the compensated system satisfies the roll angle and sideslip cross-coupling specifications at the expense of sideslip tracking performance. Though the compensated system tracks the sideslip command input β_{cmd}

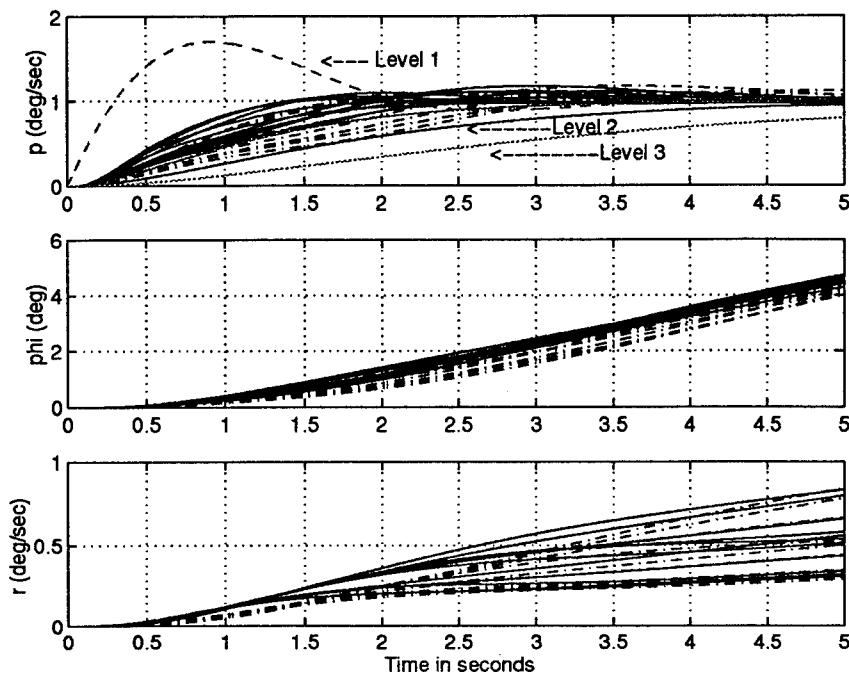


Figure 6.34 Roll Unit Step Response of Compensated System Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} < 150 \text{ lbs}/\text{ft}^2$) [1 of 3]

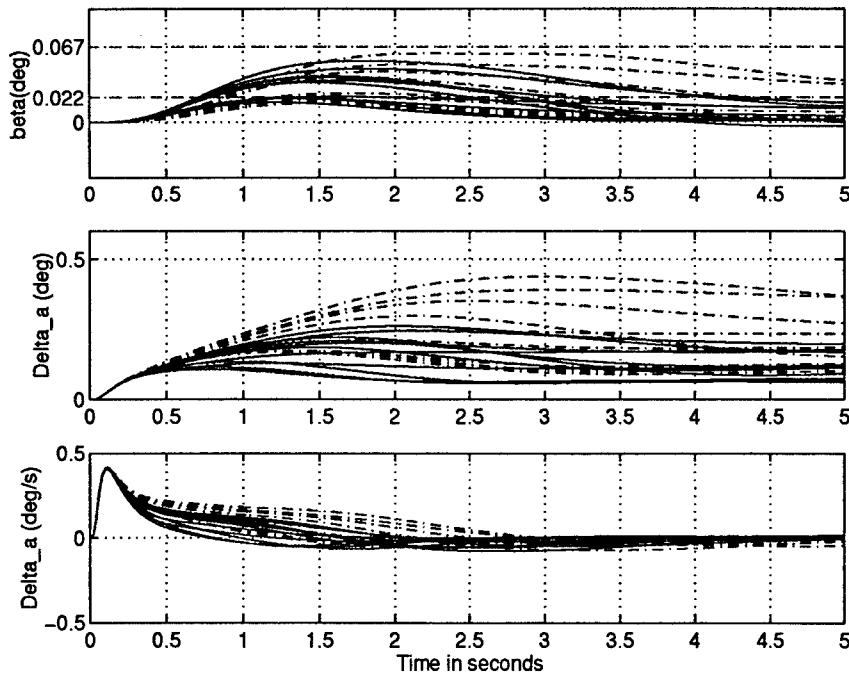


Figure 6.35 Unit Roll Step Response of Compensated System Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} < 150 \text{ lbs}/\text{ft}^2$) [2 of 3]

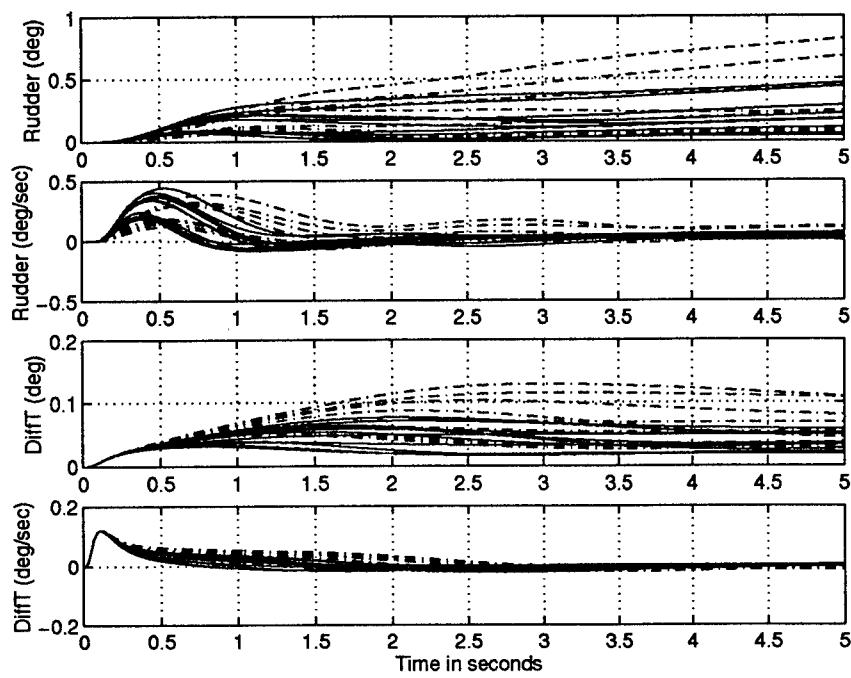


Figure 6.36 Unit Roll Step Response of Compensated System Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} < 150 \text{ lbs}/\text{ft}^2$) [3 of 3]

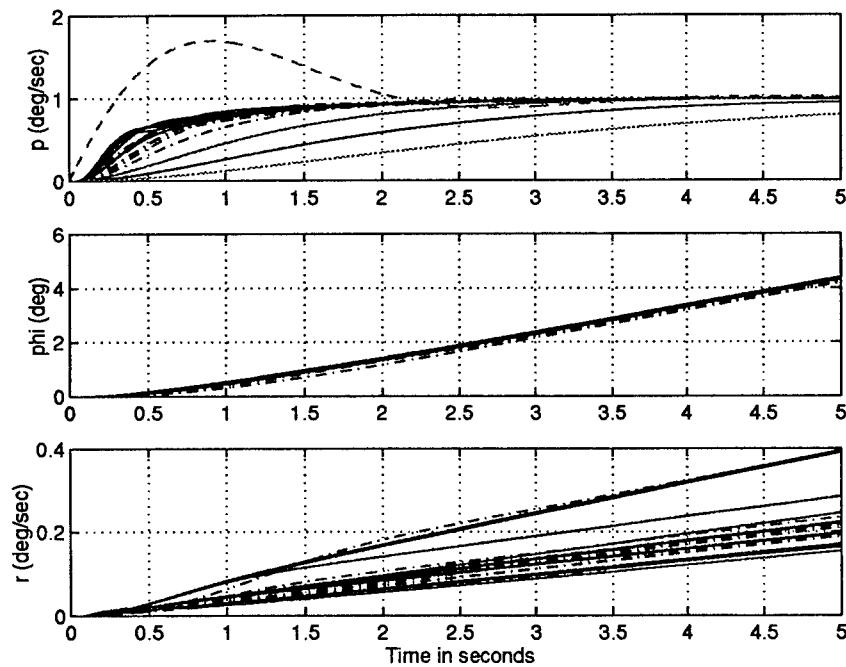


Figure 6.37 Unit Roll Step Response of Compensated System Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} > 150 \text{ lbs}/\text{ft}^2$) [1 of 3]

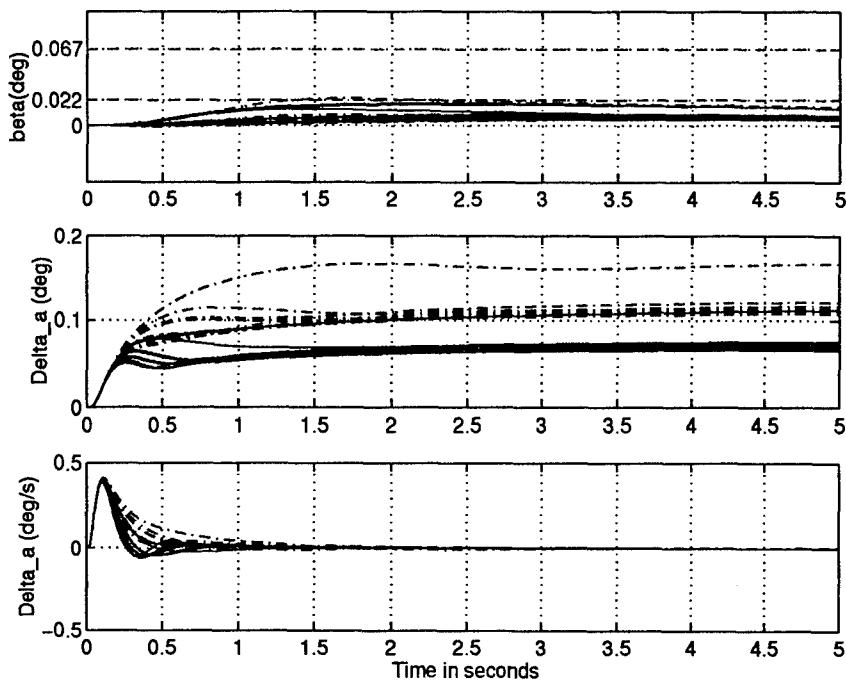


Figure 6.38 Unit Roll Step Response of Compensated System Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} > 150 \text{ lbs}/\text{ft}^2$) [2 of 3]

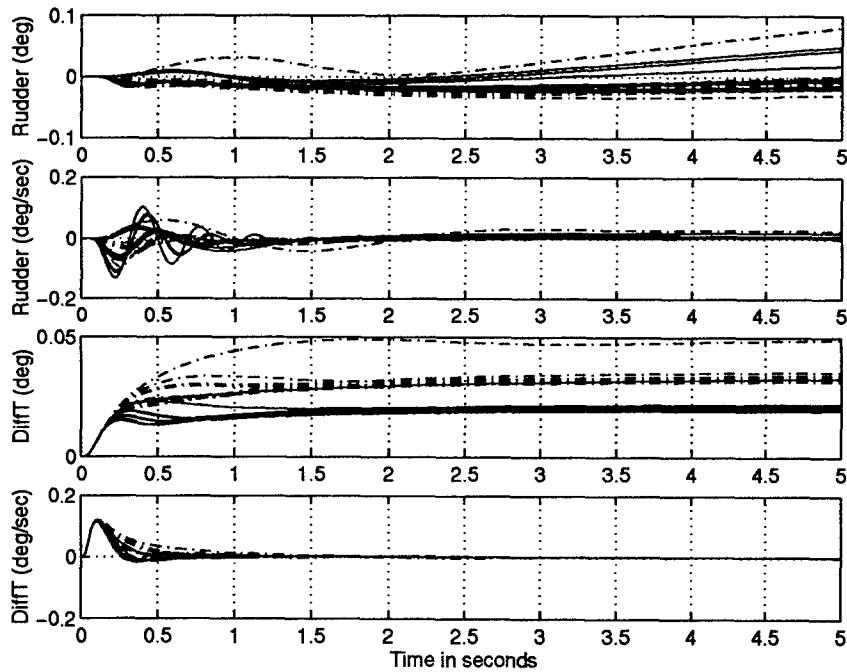


Figure 6.39 Unit Roll Step Response of Compensated System Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} > 150 \text{ lbs}/\text{ft}^2$) [3 of 3]

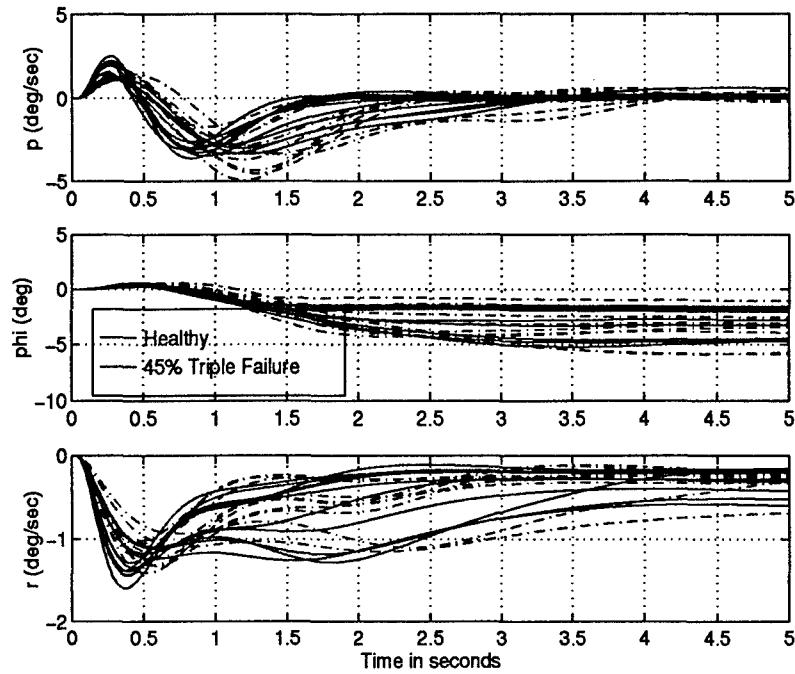


Figure 6.40 Unit Beta Step Response of Compensated System Healthy Aircraft and 45% Triple Failure Plants [1 of 3]

with zero steady-state error, these responses are sluggish. However, this sluggishness is accepted for a few reasons: first, the pilot rarely commands a sideslip angle so the necessity of a fast β response is mitigated, and second, deleterious β cross-coupling is accentuated given a faster β response.

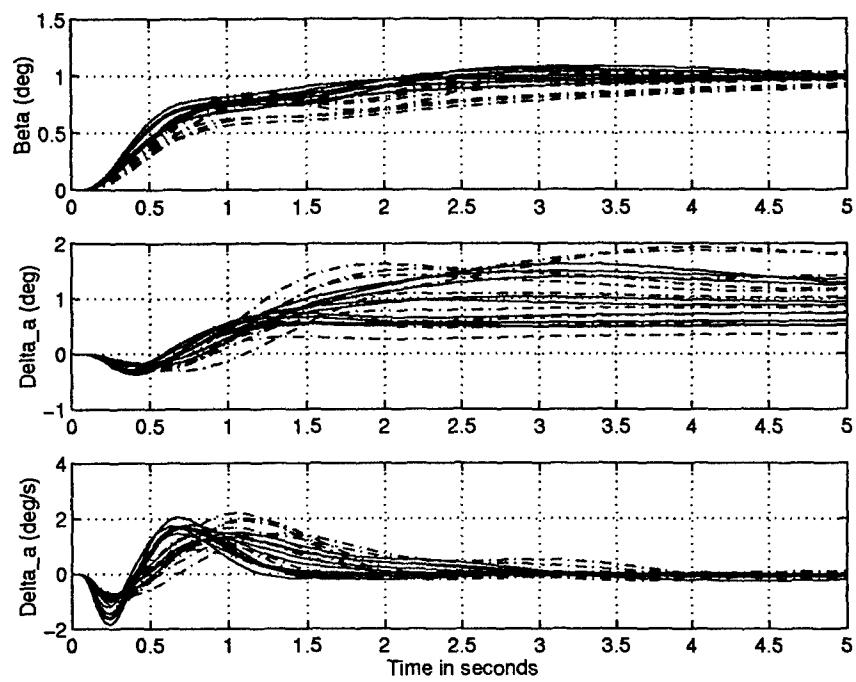


Figure 6.41 Unit Beta Step Response of Compensated System Healthy Aircraft and 45% Triple Failure Plants [2 of 3]

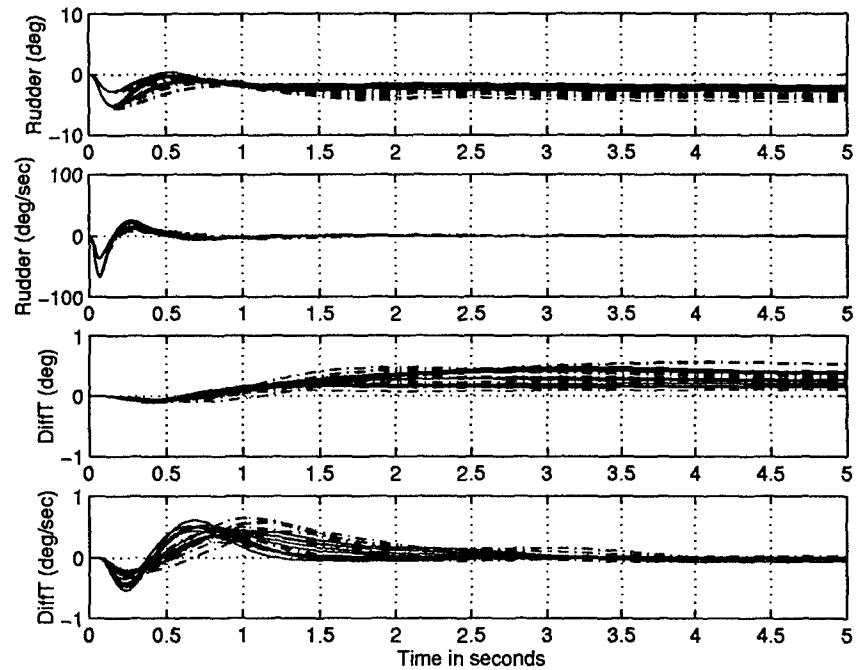


Figure 6.42 Unit Beta Step Response of Compensated System Healthy Aircraft and 45% Triple Failure Plants [3 of 3]

6.2.2 Maximum Command Gradients. Equations (6.15) through (6.20) determine the maximum allowable command input without causing rate and deflection saturations, while Eqs. (6.21) and (6.22) represent the minimum command input necessary to satisfy the roll angle performance criteria. The unit step responses found in Figs. (6.34) through (6.42) provide the data necessary to generate the maximum command gradients for the roll and sideslip channels. These gradients are found in Figs. 6.43 and 6.44.

$$\frac{60}{\dot{\delta}_{ail_{max}}} \quad (6.15)$$

$$\frac{60}{\dot{\delta}_{rud_{max}}} \quad (6.16)$$

$$\frac{60}{\dot{\delta}_{DT_{max}}} \quad (6.17)$$

$$\frac{20}{\dot{\delta}_{ail_{max}}} \quad (6.18)$$

$$\frac{30}{\dot{\delta}_{rud_{max}}} \quad (6.19)$$

$$\frac{20}{\dot{\delta}_{DT_{max}}} \quad (6.20)$$

$$\frac{360}{\dot{\phi}_{(2.8sec)}} \quad (6.21)$$

$$\frac{60}{\dot{\phi}_{(1sec)}} \quad (6.22)$$

The maximum roll command gradient boundaries (See Fig. 6.43) are conspicuously more restrictive than the gradient proposed by Phillips. The rudder and differential tail, rate and deflection saturation restrictions are not limiting factors in the overall roll gradient design. The aileron saturation restrictions, however, prove to be dominant and consequently are the only saturation boundaries identified on the figure. The aileron experiences rate and deflection saturation before achieving the 90 degree roll performance requirement. Though Phillips manipulated the maximum command gradient under the saturation boundaries and above the roll performance restrictions, in this design a more aggressive approach is taken. The maximum roll command gradient noted by the solid line on Fig. 6.43 violates

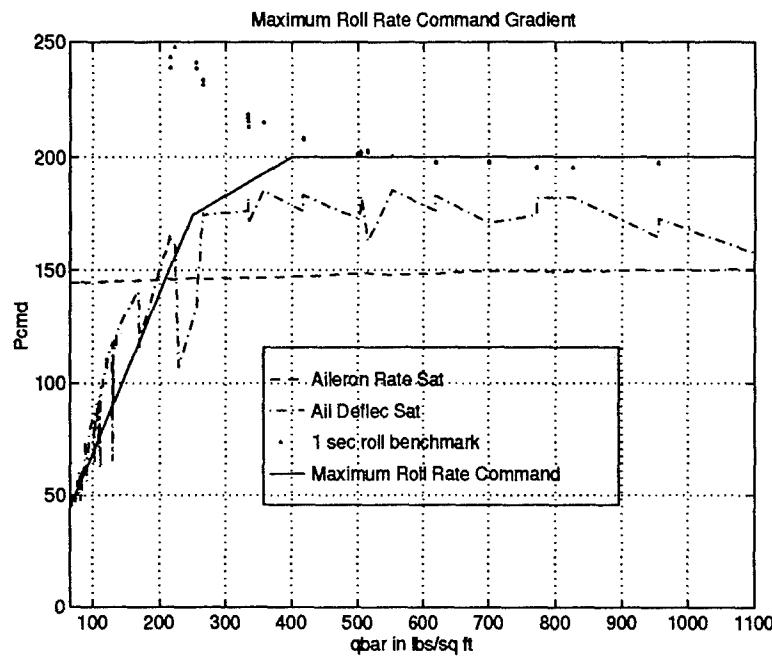


Figure 6.43 Maximum Roll Command Gradient

the rate saturation limits over most of the dynamic pressure range and violates the deflection saturation limits for dynamic pressures in excess of $150 \text{ lbs}/\text{ft}^2$. These boundaries are selectively either intersected or ignored in an attempt to improve the roll performance of the aircraft. However, it is vital for the sanctity of feedback to limit the duration of control effector saturation. If the system remains in saturation long enough, the feedback path is eliminated causing the system to go 'open-loop', and possibly unstable. Simulations of the lateral design with the maximum command gradients in place are employed to settle these performance and stability issues.

As anticipated from the unit sideslip time response analysis, the rudder rate and deflection saturation limits dominated the maximum sideslip command gradient boundaries. Since the rudder rate saturates for such a relatively small command input and previous attempts at violating the rate limits have been successful, the maximum command gradient denoted by the solid line in Fig. 6.44 is designed to exceed the rudder rate limits. Like the roll input gradient, the performance and stability issues are settled via the time simulations.

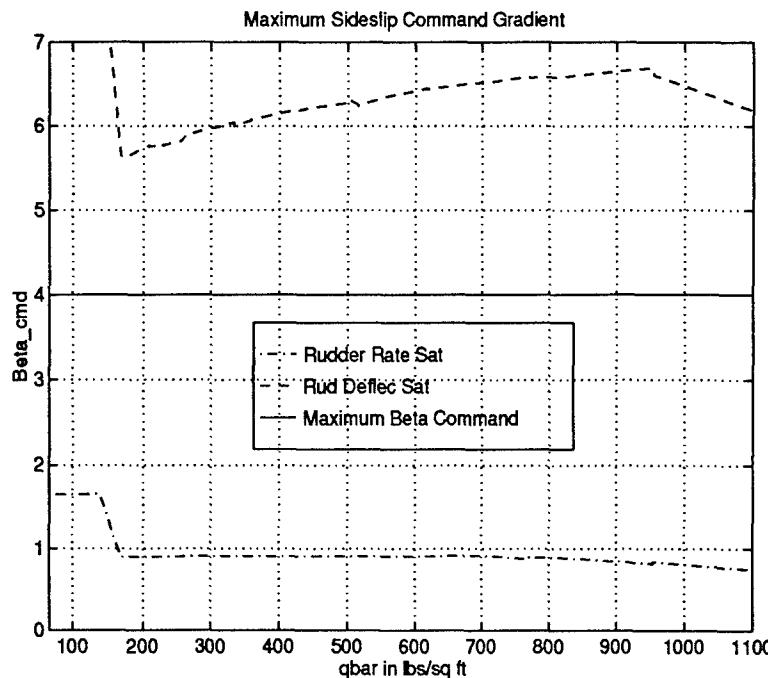


Figure 6.44 Maximum Sideslip Command Gradient

6.3 Design Validation

The final step in the lateral/directional design process is to verify that the compensated system satisfies the frequency and time domain stability, tracking, and external disturbance specifications established earlier in this chapter.

6.3.1 Stability Validation.

6.3.1.1 Sideslip Channel. None of the 398 open loop sideslip transmission functions in Fig. 6.45 transect the 6 dB constant magnitude contour, consequently the stability criteria for the sideslip channel is satisfied.

6.3.1.2 Roll Channel. The roll compensator satisfies the 6 dB stability contour with ease in Fig. 6.46. Though the gain can be increased approximately 10 dB without violating the contour, the rate and deflection saturation limits impose more restrictive requirements on the compensator gain.

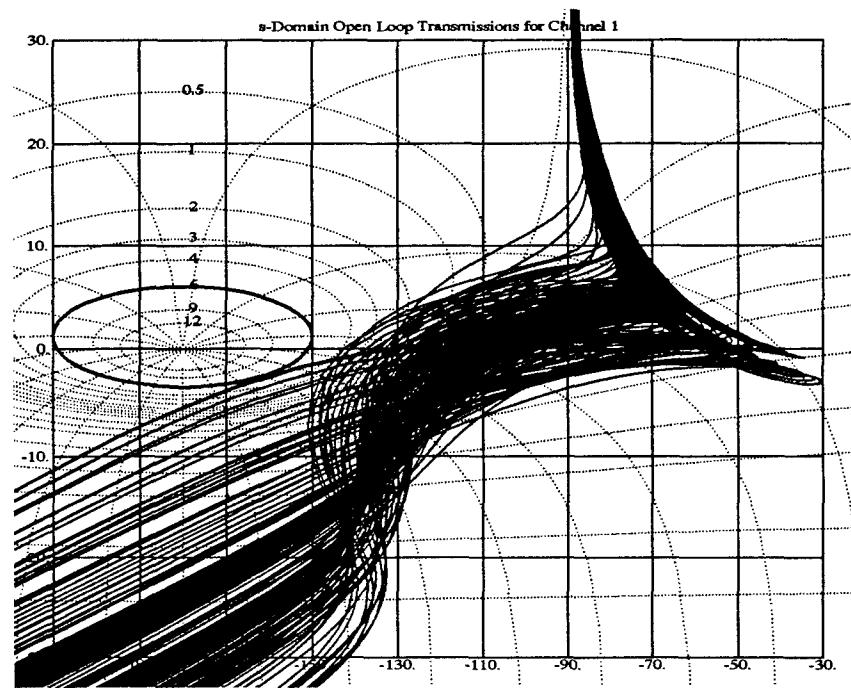


Figure 6.45 QFT Stability Validation for the Sideslip (β) Channel

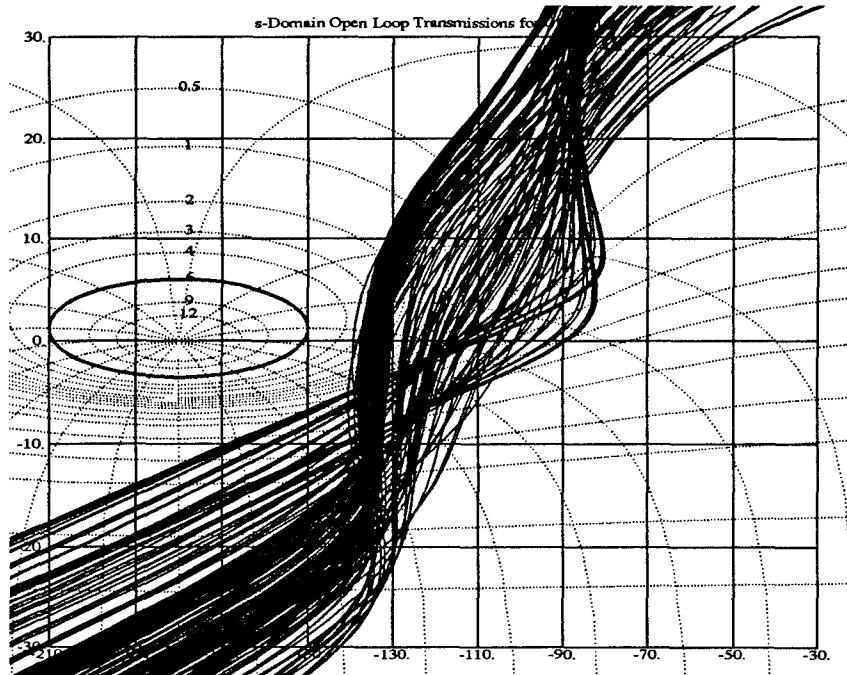


Figure 6.46 QFT Stability Validation for the Roll (p) Channel

6.3.2 Tracking Validation. The tracking validation plots found in Figs. 6.47 and 6.48 represent the culmination of MILSTD 1797A specifications and the utilization of engineering judgement into achieving a viable full envelop robust control design for the VISTA F-16 experiencing control effector failures. The tracking specifications for the $\text{Beta}_{out}/\text{Beta}_{cmd}$ MISO equivalent system are arbitrarily selected to satisfy QFTCAD as discussed in section 6.1.2.1. The time simulations, therefore, are relied upon to determine if the design provides suitable tracking for this system. $\text{Beta}_{out}/\text{Roll}_{cmd}$ MISO system meets the 0.0607 degree cross-coupling specification for all of the high dynamic pressure plants in Fig. 6.48 and for the vast majority of the low dynamic pressure plants in Fig. 6.47. The $\text{Roll}_{out}/\text{Beta}_{cmd}$ system however does not meet the -11 dB specification in either the low or high \bar{q} ranges, and validation of this system is left for the time responses. Finally, the $\text{Roll}_{out}/\text{Roll}_{cmd}$ MISO system meets or exceeds all applicable specifications defined in section 6.1.2.1. The majority of the healthy plants identified by the solid lines in both figures meet the Level 1 tracking specification, while only the low \bar{q} failed plants in Fig. 6.48 violate the Level 2 tracking bounds. This droop in the roll tracking response can be attributed to the interaction of the dutch roll damper and sideslip feedback at low dynamic pressures. In general, all the plants, healthy and failed, low as well as high dynamic pressure meet or exceed the Level 3 tracking requirement.

6.3.3 External Disturbance Rejection Validation. The external disturbance validation plots in Fig. 6.49 are disceving due to a subtlety of the external disturbance modeling process (Chap. IV). Traditionally the external disturbance rejection plot represents how the system responds to a unit step external disturbance input. However in this design, the external disturbance magnitude is enhanced by the model (See Eqs. (4.72) and (4.74)). So a unit step external disturbance input in this design, represents the effect of applying a 5 degree stabilator deflection. In other words, the external disturbance rejection plots in Fig. 6.49 are approximately 14 dB greater then they should be. After reducing each of these figures by 14 dB, the β responses (MISO(1,1)) are within acceptable limits, while some p responses (MISO(2,1)) remain outside acceptable limits. Finally, the external disturbance simulations are necessary to determine if the trouble plants can be controlled by a human pilot.

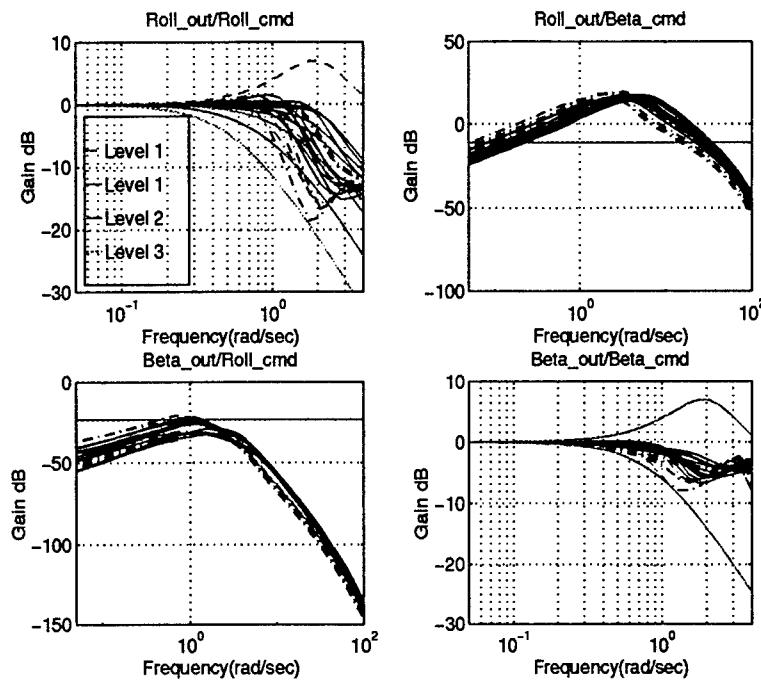


Figure 6.47 QFT Tracking Validation for the Lateral/Directional Channel ($\bar{q} < 150$ lbs/ft^2)

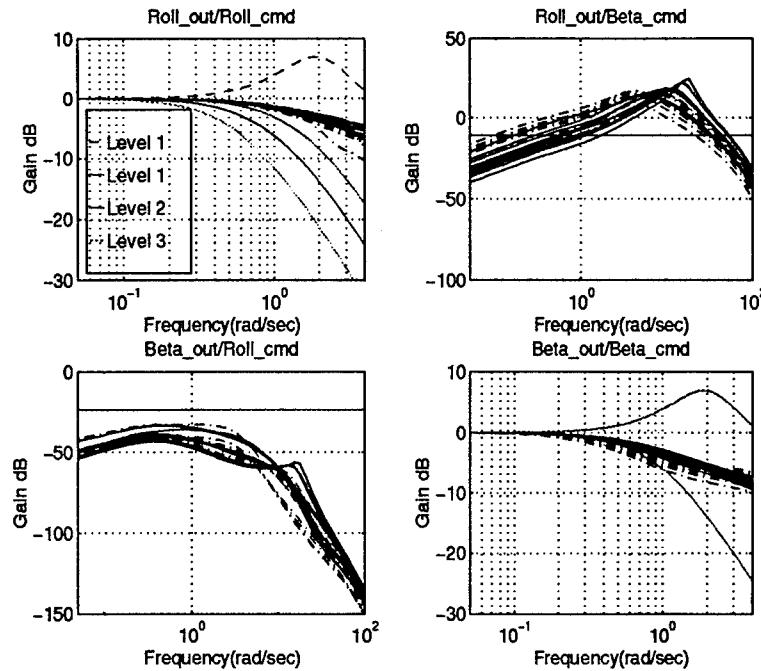


Figure 6.48 QFT Tracking Validation for the Lateral/Directional Channel ($\bar{q} > 150$ lbs/ft^2)

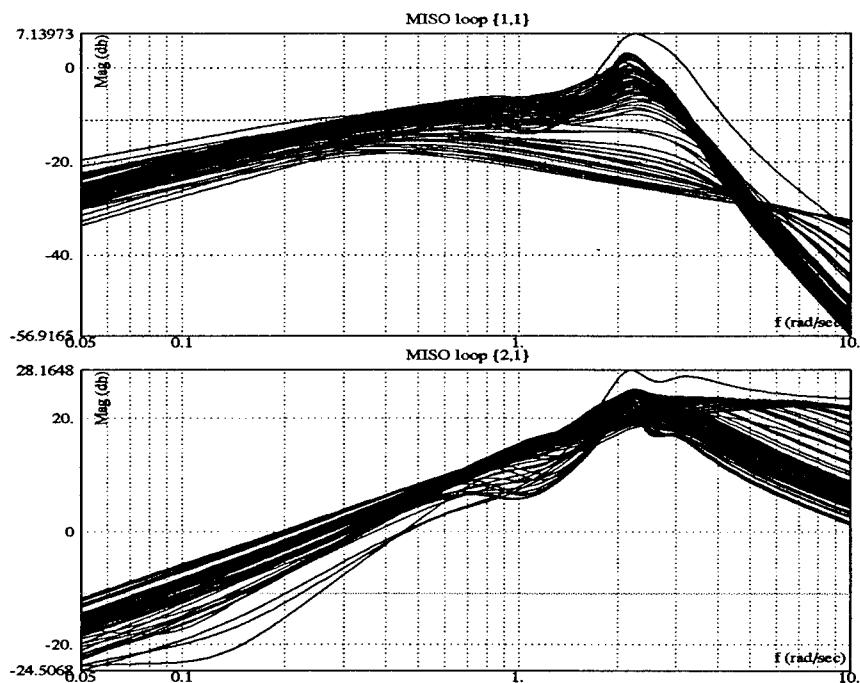


Figure 6.49 QFT External Disturbance Validation

6.3.4 Time Domain Validation. The time domain validation verifies that the FCS can meet time domain specifications when realistically high amplitude inputs, and rate and deflection saturation limitations are applied. The roll and sideslip tracking, and external disturbance responses are examined in the following sections, and the tabular data associated with these plots can be found in Appendix D.

6.3.4.1 Roll Tracking Responses. Figures 6.50 through 6.55 demonstrate that the system does indeed maintain stability, even though the extreme low \bar{q} failed plants saturate the aileron deflection. The low \bar{q} cases however do not meet the roll angle performance criteria identified on Fig. 6.50. There is simply insufficient control authority available at low dynamic pressure to adhere to these MILSTD specifications. Though this is disconcerting, Phillips was also unable to achieve these performance specifications and he was only concerned with the healthy plant set. Furthermore, Fig. 6.51 indicates that the 6 degree sideslip specification has been satisfied, while it also confirms the authenticity of the command gradient boundaries. Recall that for dynamic pressure less than $150 \text{ lbs}/\text{ft}^2$ the maximum roll command input does not exceed the aileron rate limits.

The high dynamic pressure plants found in Figs. 6.53 through 6.55 also verify that the system can maintain stability despite aileron and differential tail saturation. The high dynamic pressure plants also demonstrate enhanced roll performance and beta decoupling. The majority of the plants including the failure plants satisfy the 360 degree roll angle requirement, and all of the plants meet the 6 degree maximum sideslip specification. The roll command gradient proves that the 90 degree roll angle requirements are the most difficult restriction to satisfy. However, as Appendix C supports, a majority of the healthy plants met or exceeded this criteria as well.

6.3.4.2 Sideslip Tracking Responses. Unlike the roll tracking responses, both the low and high \bar{q} plants are grouped together on Figs. 6.56, 6.56, and 6.56. The failed sideslip tracking simulations in Fig. 6.56 are clearly less responsive than the healthy aircraft plants identified by the solid lines. Also, the rudder deflection remains within the saturation limits for all plant cases, while the rudder rate does saturate. For some

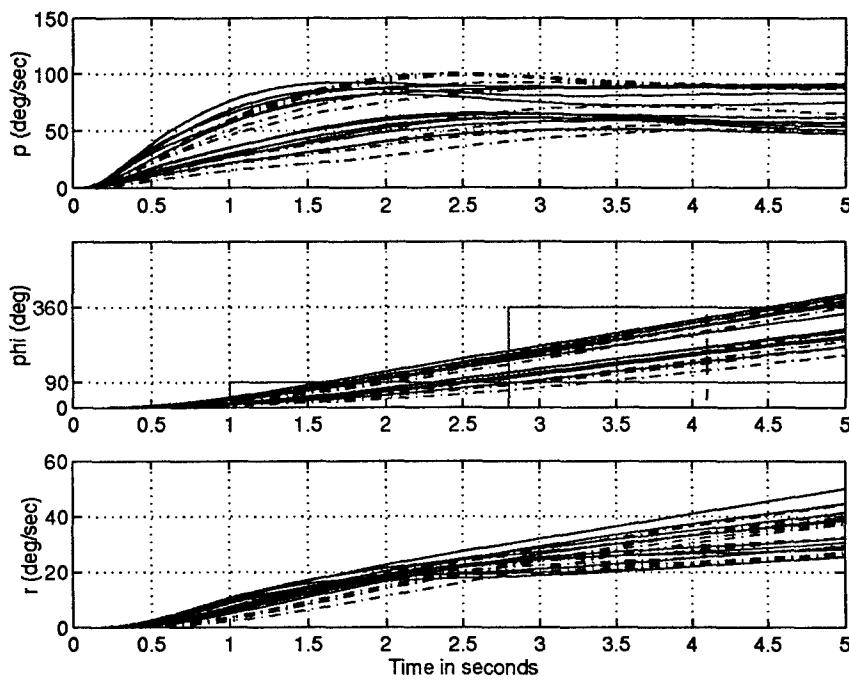


Figure 6.50 Maximum Roll Gradient Step Response of Compensated System, Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} < 150 \text{ lbs}/\text{ft}^2$) [1 of 3]

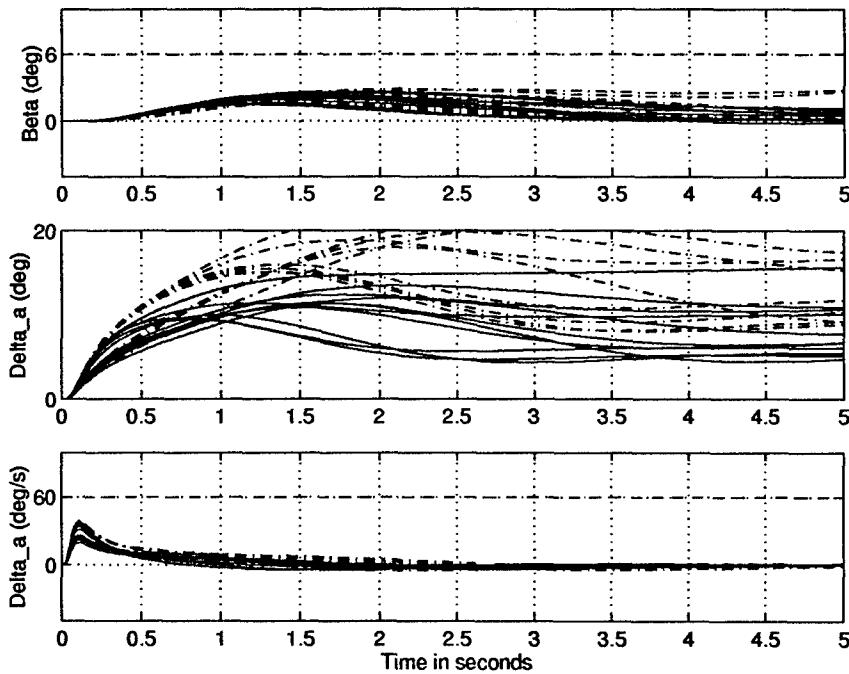


Figure 6.51 Maximum Roll Gradient Step Response of Compensated System, Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} < 150 \text{ lbs}/\text{ft}^2$) [2 of 3]

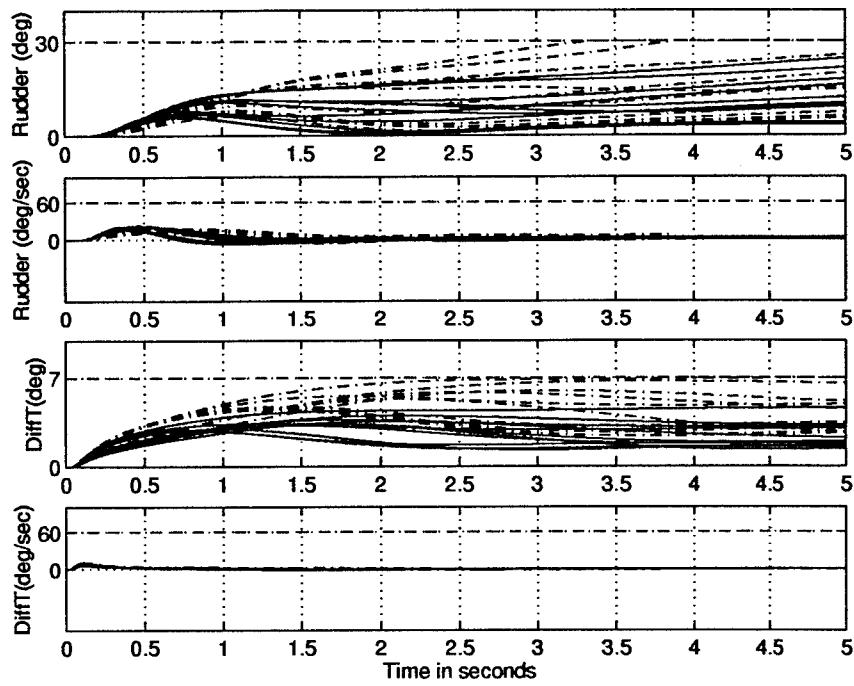


Figure 6.52 Maximum Roll Gradient Step Response of Compensated System, Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} < 150 \text{ lbs}/\text{ft}^2$) [3 of 3]

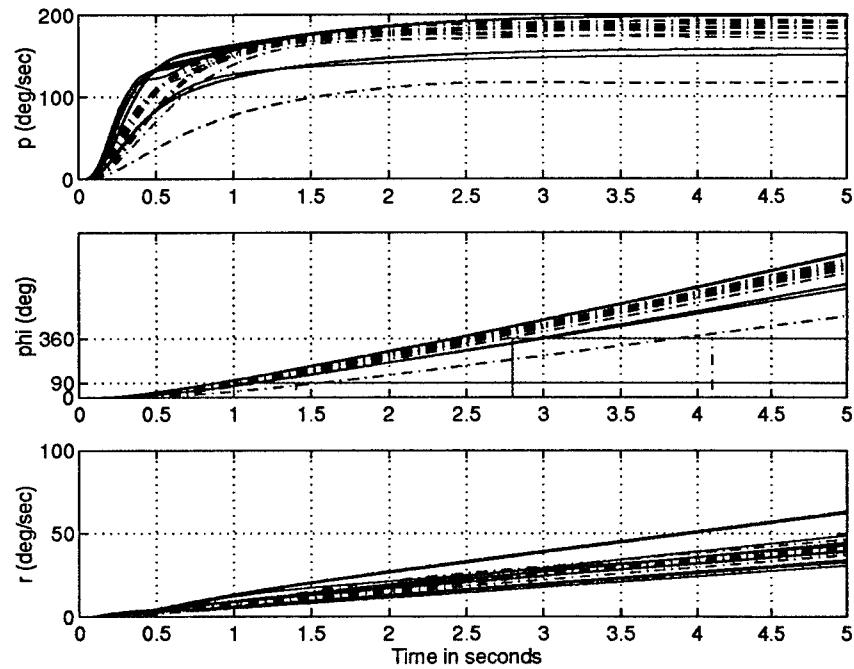


Figure 6.53 Maximum Roll Gradient Step Response of Compensated System, Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} > 150 \text{ lbs}/\text{ft}^2$) [1 of 3]

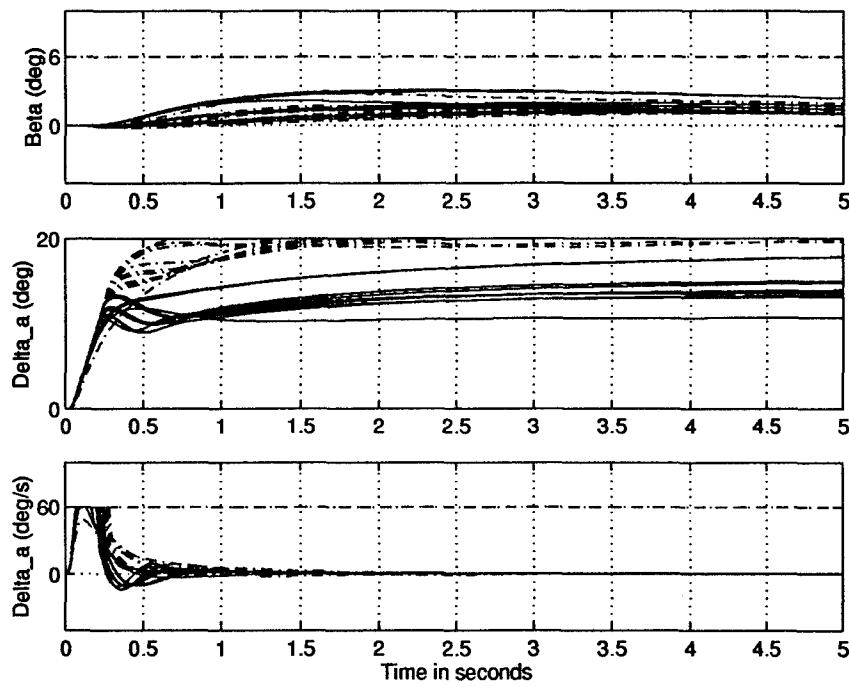


Figure 6.54 Maximum Roll Gradient Step Response of Compensated System, Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} > 150 \text{ lbs/ft}^2$) [2 of 3]

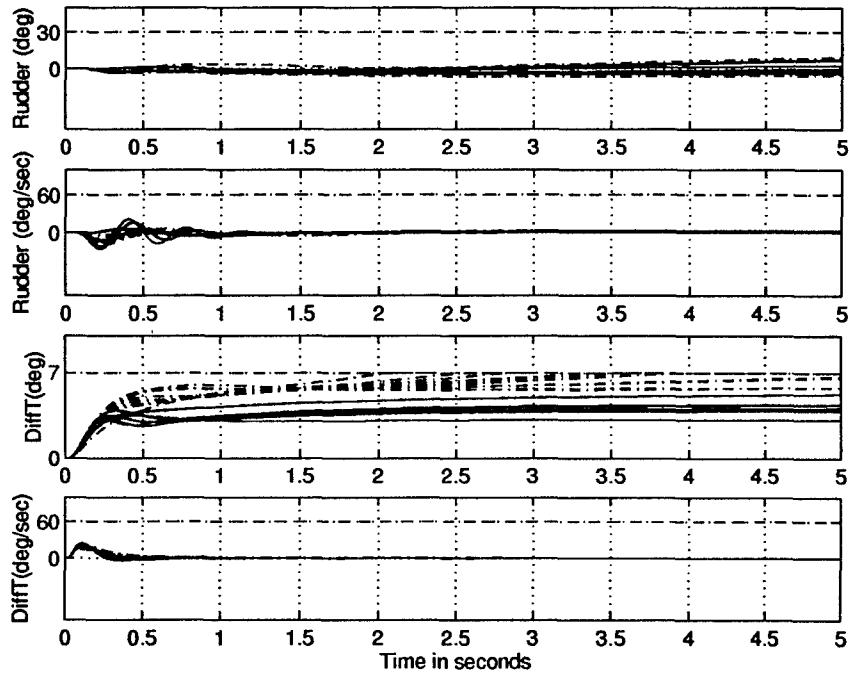


Figure 6.55 Maximum Roll Gradient Step Response of Compensated System, Healthy Aircraft and 45% Triple Failure Plants ($\bar{q} > 150 \text{ lbs/ft}^2$) [3 of 3]

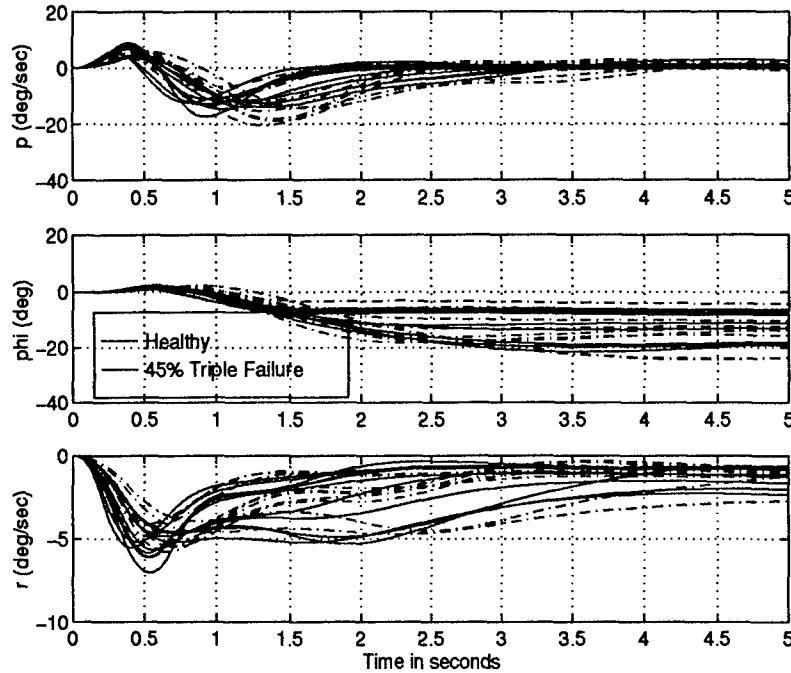


Figure 6.56 Maximum Sideslip Gradient Step Response of Compensated System, Healthy Aircraft and 45% Triple Failure Plants [1 of 3]

plants this saturation exceeds 0.5 seconds. Fortunately, the system maintains stability, and verifies that the aggressive β command gradient is warranted.

6.3.4.3 External Disturbance. Time domain external disturbance analysis is imperative to validate the disturbance models, and to determine how the disturbance effects the entire system. Recall that the external disturbance is introduced to appropriately model the asymmetric horizontal stabilator deflection problem created from an elevator failure. If the system is wired correctly then the aileron and differential tail should deflect in the negative direction (based on the sign convention established in Chap. III) to counter a positive roll- rate. Also, the rudder should deflect in the positive direction to counter a positive sideslip angle disturbance. The simulations found in Figs. 6.59 through 6.64, indeed confirm that the system responds appropriately to the external disturbance.

Since the external disturbance specifications are not achieved in the design of the QFT compensator, the disturbance rejection simulations are particularly important to settle some pertinent stability and control issues. Acceptable disturbance rejection requires

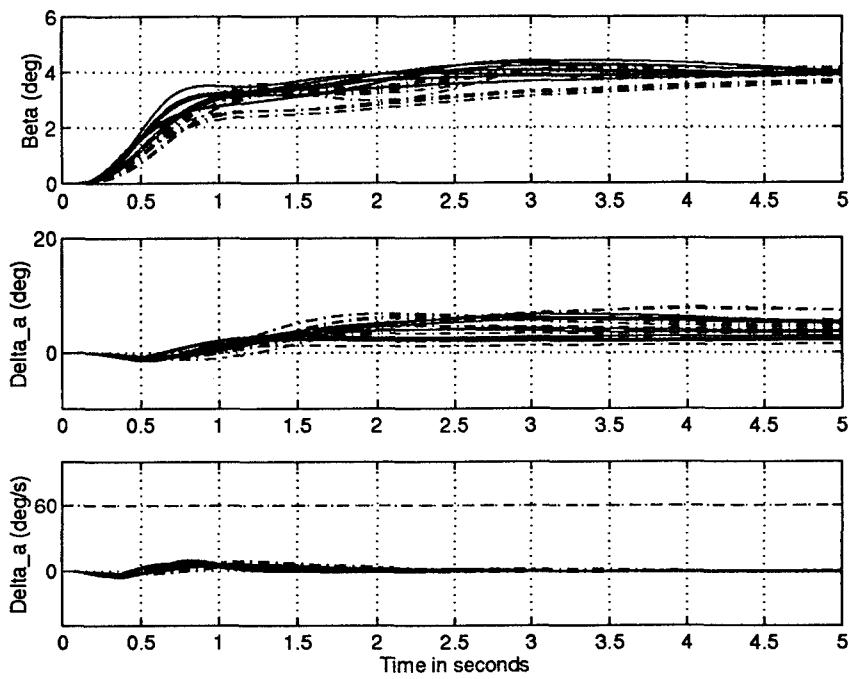


Figure 6.57 Maximum Sideslip Gradient Step Response of Compensated System, Healthy Aircraft and 45% Triple Failure Plants [2 of 3]

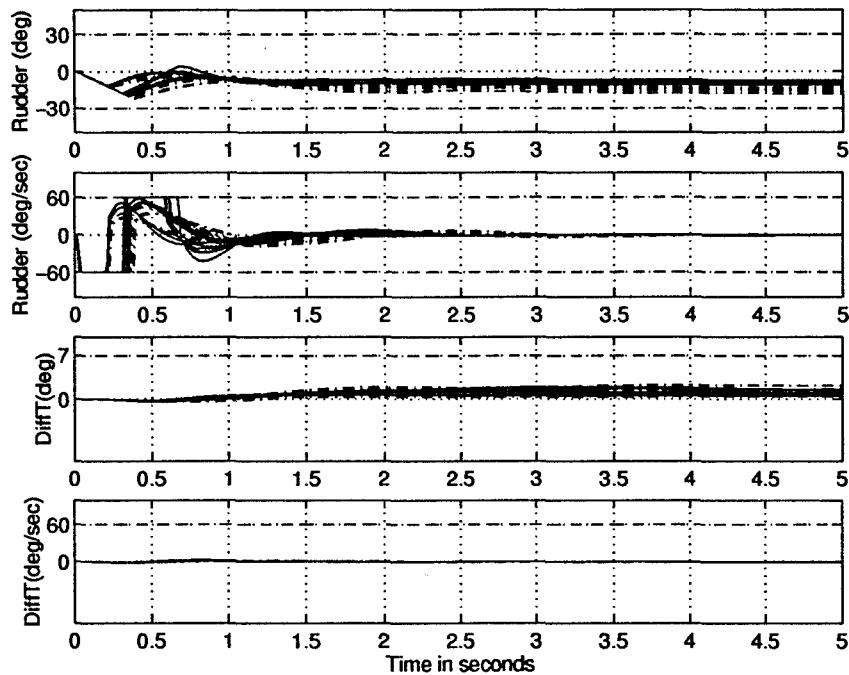


Figure 6.58 Maximum Sideslip Gradient Step Response of Compensated System, Healthy Aircraft and 45% Triple Failure Plants [3 of 3]

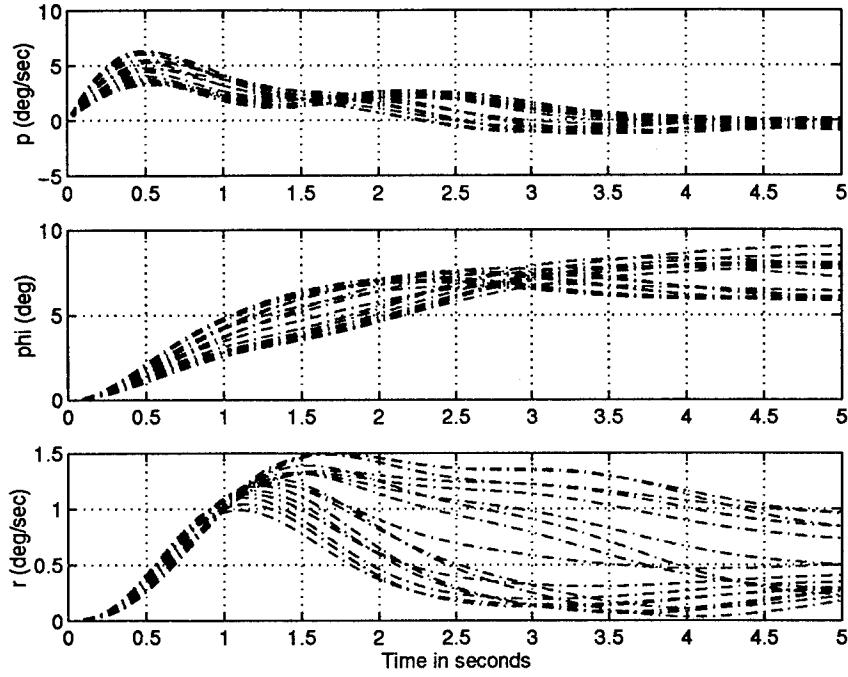


Figure 6.59 Disturbance Step Response of Compensated System, 45% Triple Failure Plants ($\bar{q} < 150 \text{ lbs}/\text{ft}^2$) [1 of 3]

that the system maintain stability, the commanded responses settle within the five second time period of interest, and the control effectors avoid rate and deflection saturation limits. The external disturbance rejection simulations for the low dynamic pressure found in Figs. 6.59, 6.60, and 6.61 clearly meet these rejection requirements.

The commanded variables, roll rate p and sideslip β , are the only variables expected to settle to zero in steady-state. The other aircraft states and control effector deflection must be evaluated in the time domain to determine if the responses are within acceptable limits. Among the most crucial of all uncontrolled states is the roll angle ϕ . Even if the roll-rate settles to zero the system may achieve a significant roll angle before the pilot can counter the disturbance. From Fig. 6.59, ϕ approaches only 9 degrees which is tolerable considering a 45% reduction in the horizontal stabilizer area.

The high dynamic pressure external disturbance time responses in Figs. 6.62, 6.63, and 6.64 exhibit superior rejection in comparison to the low \bar{q} plants. These high \bar{q} plants easily satisfy the disturbance rejection settling, stability, and saturation requirements.

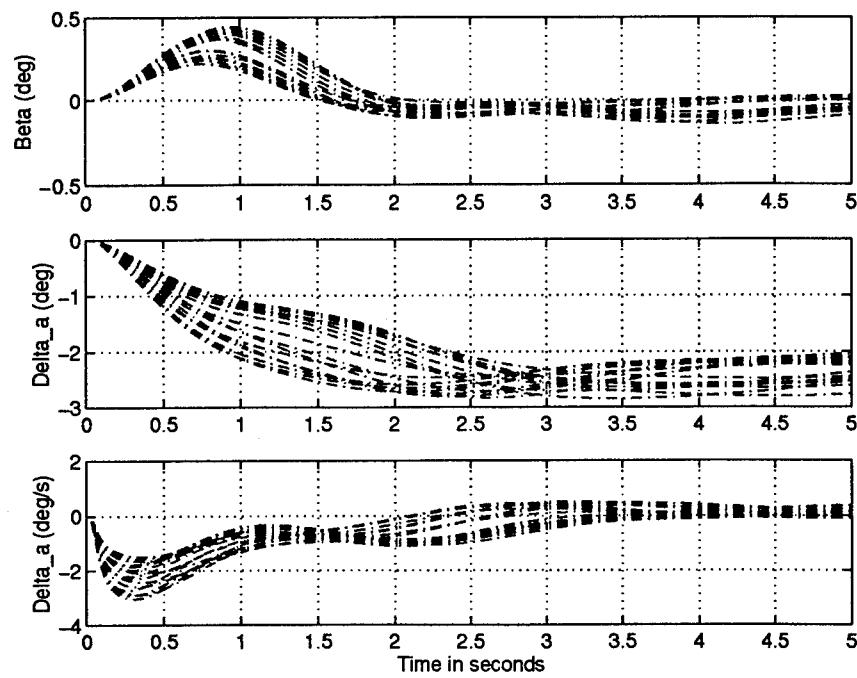


Figure 6.60 Disturbance Step Response of Compensated System, 45% Triple Failure Plants ($\bar{q} < 150 \text{ lbs}/\text{ft}^2$) [2 of 3]

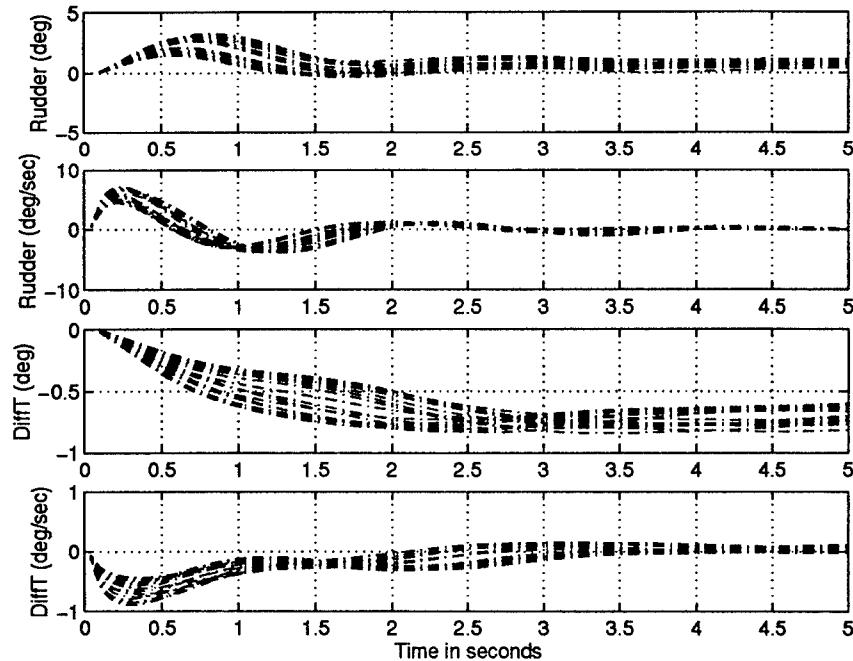


Figure 6.61 Disturbance Step Response of Compensated System, 45% Triple Failure Plants ($\bar{q} < 150 \text{ lbs}/\text{ft}^2$) [3 of 3]

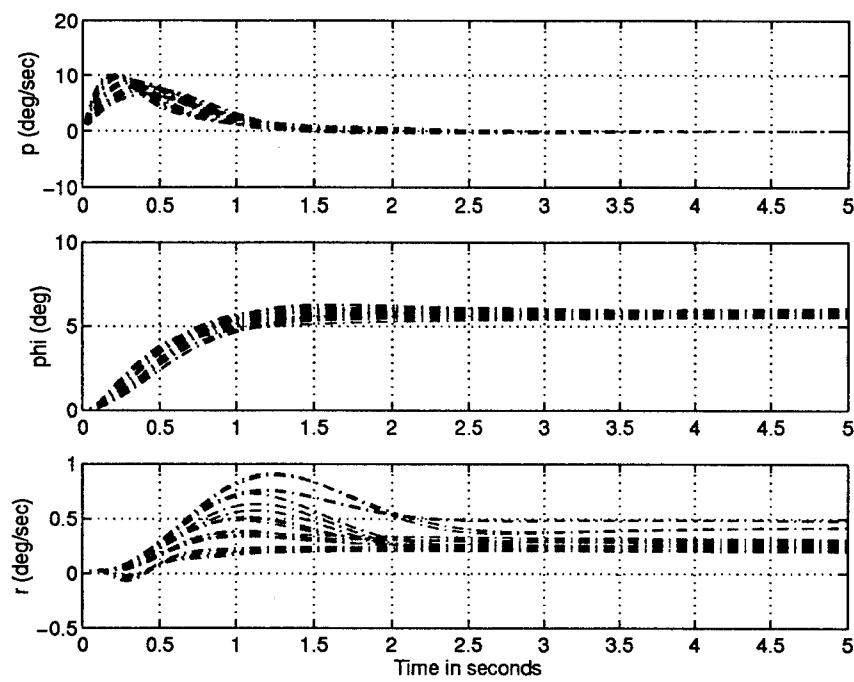


Figure 6.62 Disturbance Step Response of Compensated System, 45% Triple Failure Plants ($\bar{q} > 150 \text{ lbs}/\text{ft}^2$) [1 of 3]

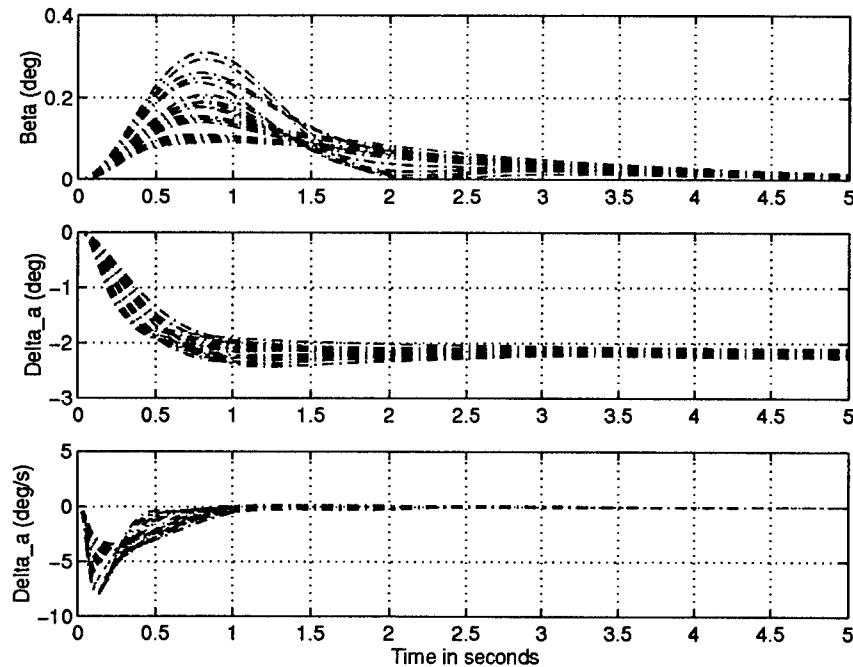


Figure 6.63 Disturbance Step Response of Compensated System, 45% Triple Failure Plants ($\bar{q} > 150 \text{ lbs}/\text{ft}^2$) [2 of 3]

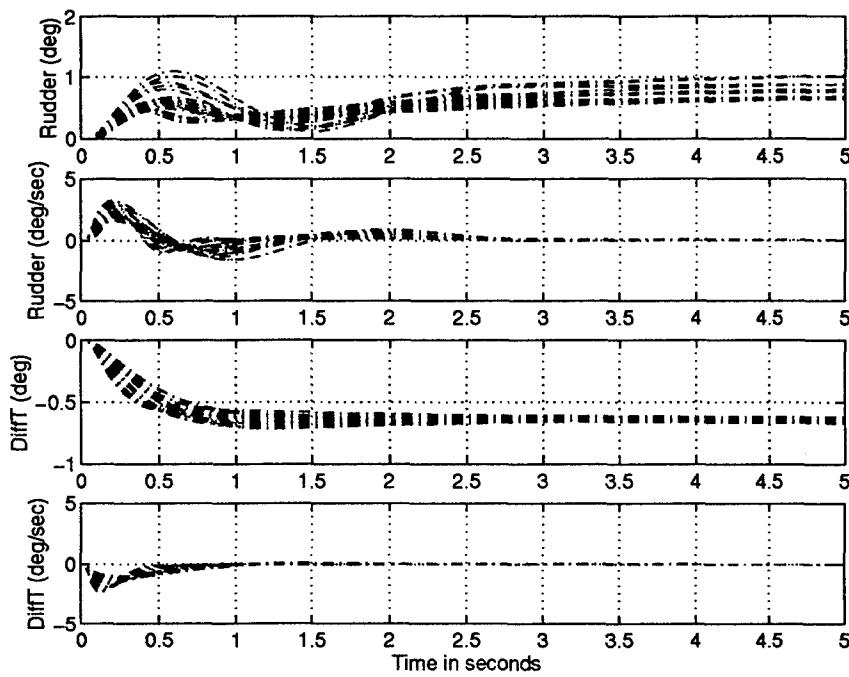


Figure 6.64 Disturbance Step Response of Compensated System, 45% Triple Failure Plants ($\bar{q} > 150 \text{ lbs}/\text{ft}^2$) [3 of 3]

6.4 Lateral/Directional Design Summary

This chapter covered the complete lateral/directional channel design process. The 2X2 MIMO QFT structure is discussed including the dutch roll damper circuit and weighting matrix \mathbf{W} . A root locus approach is taken to determine the coefficients of the washout filter, and then the focus is shifted to the development of the tracking, external disturbance, and performance specifications. From these specifications the appropriate models are generated and the failure analysis is initiated. A 45% triple failure design set is selected and the QFTCAD program is applied to form the effective plants and subsequent frequency templates. Since Phillips' plants matched the healthy plants from this design, some additional comparisons are drawn between the healthy and failed plant sets. Given these templates, the QFT bounds are formed and the failure effects on tracking, cross-coupling, and stability are examined. These boundaries guided the development of the QFT roll and sideslip compensators. Time simulations are applied to this FCS design, the responses are discussed, and the maximum command gradients are formed. Finally, the lateral/directional FCS in Fig 6.65 is validated with realistic command inputs and satura-

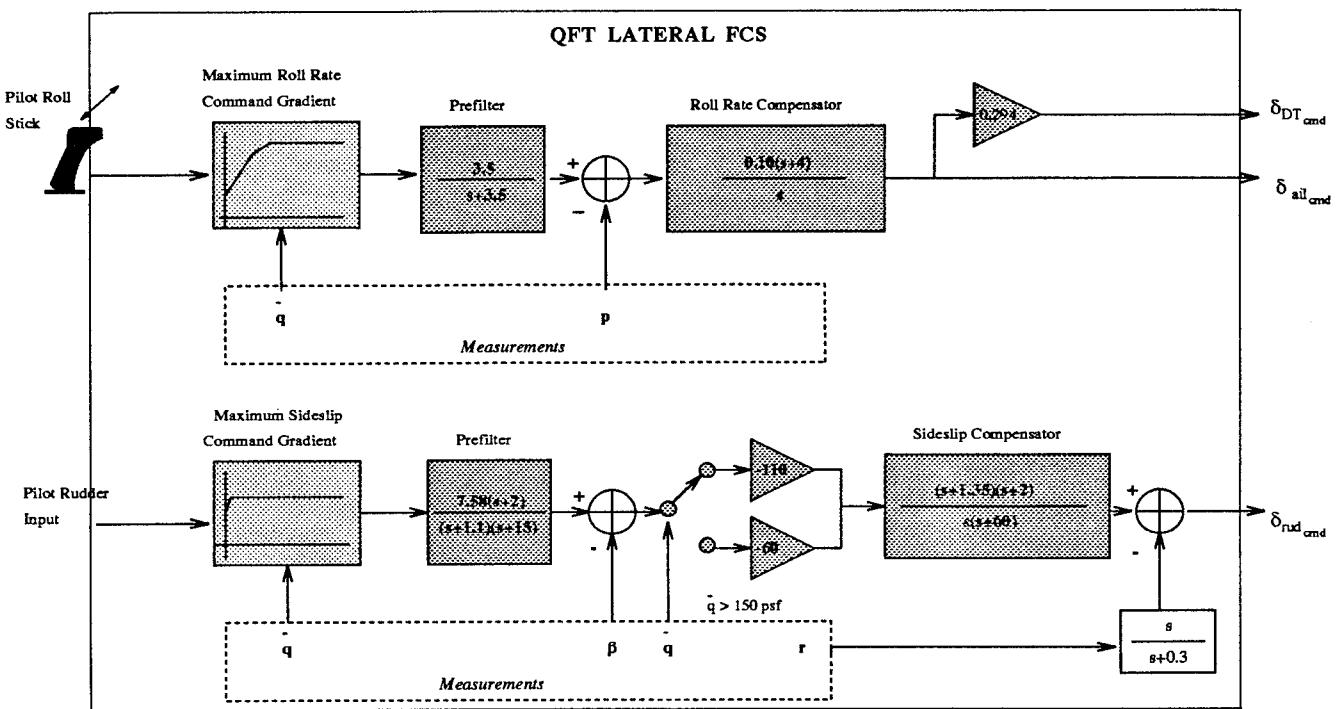


Figure 6.65 Final QFT Lateral FCS

tion limitations. A more complete evaluation of the design objectives and failure analysis follows in Chap. VII.

VII. Conclusions and Recommendations

This chapter provides closure for this research effort by presenting overall design conclusions and recommendations for future exploration.

7.1 Conclusions

The primary and secondary goals established in Chap. I have been achieved. Specifically, a realistic robust FCS for the full subsonic envelope of the VISTA F-16 has been developed which is tolerant to flight control effector failures from the outset. Furthermore, the maximum control effector failure level that a successful QFT design can accommodate has been determined.

Thus, the compensated system clearly met the MILSTD Level 1 flying qualities specifications for the unimpaired aircraft at high dynamic pressure flight conditions in both the longitudinal and lateral/directional channels, which is tantamount to maintaining nominal flight control. Furthermore, for 25% stabilator failure in the longitudinal channel, and the 45% triple effector failure cases in the lateral/directional channel at least Level 3 flying qualities specifications were achieved. The majority of the impaired aircraft for the high dynamic pressure flight conditions exhibit Level 1 or 2 flying qualities, while only the worst case low dynamic pressure failed plants exhibit Level 3 flying qualities.

The secondary goal was to determine the maximum control effector failure level the proposed QFT design could incur. In general, it was more difficult to achieve the performance specifications in the longitudinal channel than in the lateral/directional channel. The static instability of the VISTA F-16, coupled with the restrictions placed on the compensator, required significant attention in the longitudinal design. Though Phillips [15] was able to avoid saturating the control surfaces while simultaneously achieving the performance benchmarks, a more aggressive approach was necessary in this design. The command gradient was designed to violate the stabilator saturation rate limits, while avoiding the deflection limits. The stabilator deflection limits were uncompromising. If they were violated then the system becomes unstable. This instability indicated that a successful QFT FCS design for damage levels greater than 25% is unattainable, which coincides

with the difficulties encountered during the loop shaping process. The lateral/directional channel, however, did not demonstrate the same instability, or loop shaping difficulties experienced in the longitudinal design. A more aggressive command gradient was required for both the roll and sideslip compensators, but the system maintained stability for both control effector deflection and rate saturation. The only constraint limiting the accommodation of higher failure levels in the lateral/directional channel is sideslip angle tracking and disturbance rejection. If stability was the only applicable requirement, a successful QFT FCS design for a damage level in excess of 45% triple failure may be attainable.

The compensators for both channels (repeated in Eqs. 7.1, 7.2, and 7.3) adhere to the guidelines established in Chap II. The longitudinal and lateral/directional compensators are both second-order transfer functions, with bandwidths less than 60 rps, and physically realizable steady-state gains. In addition, gain scheduling was applied discriminately. Scheduling was only necessary to achieve the required turn coordination specifications in the directional channel. Overall, the three compensators and prefilters are remarkably elegant considering the extent of the uncertainty inherent in this problem.

$$G_{C^*} = \frac{4.45(s + 2.3)(s + 12.5)}{s(s + 43)} \quad F_{C^*} = \frac{0.25(s + 6)}{s + 1.5} \quad (7.1)$$

$$G_p = \frac{0.10(s + 4)}{s} \quad F_p = \frac{7.58(s + 2)}{(s + 1.1)(s + 15)} \quad (7.2)$$

$$G_\beta = \frac{K_\beta(s + 1.35)(s + 2)}{s(s + 60)} \quad F_\beta = \frac{3.5}{(s + 3.5)} \quad (7.3)$$

This research further promotes the C^* controlled variable concept in order to embed flying quality specifications into the design, and enhance system performance. Properly selecting the blending of the q and N_z components of C^* proves to be extremely important. The “asymptotic” gradient, which more accurately represents the pilot’s tracking tendencies, has been proven to actually decrease the equivalent plant uncertainty witnessed on the QFT frequency templates. Also, the C^* blending has demonstrated an intimate connection with the size and geometry of the templates for the failed plants. This connection has been thoroughly investigated in this thesis and is referred to as the “swirl effect.”

Finally, it should be noted that this design has undergone extensive testing and evaluation in both the frequency and time domains. Despite actuator saturation limitations and compensator restrictions, the design achieves the 9g and 25° angle-of-attack performance benchmarks in the longitudinal channel and the roll angle requirements for nearly all plant cases in the lateral/directional channel. In addition, the compensated system was able to maintain “feet-on-the-floor” turn coordination over the entire flight envelope.

7.2 *Recommendations*

The following recommendations are made:

- First, Phillips’ FCS design for the unimpaired aircraft should be compared to the current F-16 Block 40 flight control system. Then, this comparison should be employed to further evaluate the performance of the fault tolerant system developed in this research. It is expected that this analysis will endorse QFT as a robust design over the Block 40’s gain scheduling “point design” approach.
- The failures effected the aircraft as anticipated. The failed aircraft models required a gain increase to track a step input, while responding with greater overshoot, onset delay, and settling time than the healthy aircraft models. However, the insignificant difference between the 15% and 25% failure templates, and the relatively benign disturbance responses, imply that the failure modeling analysis may be too conservative. The failure analysis was conducted on aircraft models trimmed about a level flight condition, which may not represent the worst case failure scenario. Therefore, it is suggested that the failure modeling generated in this research should be validated with wind tunnel data, and encoded into the SRF simulation routine. Full non linear simulations can then be conducted on this fault tolerant design, and the design reevaluated.
- The C^* variable has been shown to have a dramatic and beneficial impact on both the healthy and failed FCS design process. This finding warrants additional research in developing an “optimal” C^* blend.

- Some additional time domain analysis may be appropriate for this fault tolerant system. Traditionally, only step tracking and disturbance responses are independently generated. However, a step response may not mimic a pilot's command input as well as a ramp or doublet response, and the saturation limits imposed on the control effectors may invalidate the linearity condition that allows for independent observation of the tracking and disturbance responses. Therefore, tracking simulations should be conducted with a variety of realistic command inputs while simultaneously introducing an external disturbance.
- The following enhancements are suggested for the QFTCAD program:
 1. To readily determine the difference between various plant sets, it would have been helpful in this design for QFTCAD to store and overlay frequency templates from various plant sets.
 2. In line with the previous suggestion, if a composite listing of boundary plants from each frequency template could be generated automatically, and the design continued only with this boundary set, the computational burden encountered in this design would have been reduced considerably.
 3. QFTCAD's *Mathematica* based plot functions provide little flexibility for customization, and therefore could use some improvements.
 4. A direct interface with *Matlab* to load and manipulate plant files would have obviated the need for the elaborate modeling scheme developed in Chap IV.
- The FCS developed in this research has proven that QFT can manage the level of uncertainty inherent in a fault tolerant FCS, while yielding a control system capable of maintaining nearly nominal flight performance without failures and stabilization with failures. However this robustness negatively impacts the performance of the healthy aircraft. In essence the fault tolerant FCS is designed to favor a worst case scenario, that may never occur, over the performance of the healthy aircraft. Surely the uncertainty in the design would be reduced and greater nominal performance could be achieved, if some failure detection and isolation (FDI) scheme was applied

in conjunction with the QFT approach. Thus, further research should be conducted bringing this marriage of QFT and a FDI scheme to fruition.

Appendix A. Failure Model Generation Macro

%PURPOSE

The Purpose of this program is to implement control effector failures on the VISTA F-16 AC models generated by Major Scott Phillips in his thesis. This algorithm was developed by Keating in his study of the Lambda test aircraft with minor modifications made due to the structural differences between the VISTA and the Lambda aircraft.

%ORGANIZATION

This program loads a particular AC plant from Phillips' database located in the edit_plants directory then it modifies the appropriate stability derivatives and outputs these plants to mF#.m located in the failed_plants dir where # corresponds to the SRF number of the unfailed plant.

%CONSTANTS DEFINED

```
nu = 0.90;
Se = 63.7;           %Sq ft Surface area of fully functional elevator
Sr = 11.65;          %Sq ft Surface area of fully functional rudder
Sa = 26.56;          %Sq ft Surface area of fully functional aileron
Sf = 54.8;           %Sq ft Surface area of fully functional VTail
St = 63.7;           %Sq ft Surface area of fully functional HTail
Sw = 323.2;          %Sq ft Surface area of fully functional wing
lt = 15.86;          %length from tail to Nominal Cg at FS320.654
k = 0.33;            %Aerodynamic constant
```

%SELECT DAMAGE LEVEL

```
Zeta_e = .25;
Zeta_r = 1;
Zeta_a = 1;
Zeta_rp = ((Zeta_r - 1)*Sr + Sf)/Sf ;
Zeta_ar = ((Zeta_e - 1)*St + (Zeta_a - 1)*Sa + (Zeta_r -1)*Sr
+ Sw + Sf + St)/(Sw + Sf + St) ;
```

%INPUT PLANTS

```
cd /eng1/vcacciat/Thesis/PLANTS
for u = 1:282;
    cd /eng1/vcacciat/Thesis/PLANTS/edited_plants
eval(['m' num2str(u) 'e']);
```

%Define Variables Necessary for Stability Derivative Modeling

```
A = A_VISTA;
B = B_VISTA ;
Delta_Xcg = XCG/12;
```

```

at = CLQ/ALPHA;
aw = CLQ/ALPHA;

%Define Variables Necessary for Disturbance Modeling
Kn = IXZ/IZZ;
Lambda = 1-((IXZ)^2/(IXX*IZZ));
MaxELEV = 21;
Trim=.20*MaxELEV;
Ldelta_a = B(7,4);
Zdelta_e = B(3,1);
Zalpha_dot = A(3,4);
Mdelta_e = B(2,1);
Malpha_dot = A(4,4);
k1 = U - Zalpha_dot;
k2 = (1 - Zeta_e)/Zeta_e;

%MODIFY Stability Derivatives

%%LONGITUDINAL
%%%%Cma
%%%%%Note that Delta_MA/MA is negative and the F-16 is unstable
%%%%%so the failed Cma should be of greater value than the healthy
Delta_MA =(Zeta_e-1)*nu*St*at*lt*(1-k);
MA = Sw*aw*Delta_Xcg - Zeta_e*nu*St*at*lt*(1-k);
A(4,3) = A(4,3)*(1 - (Delta_MA/MA));

%%%%Cmq
A(4,4) = A(4,4)*Zeta_e;

%%%%Cmdeltae
B(4,1) = B(4,1)*Zeta_e;

%%%%Cza
Delta_ZA =(1-Zeta_e)*nu*St*at*(1 - k);
ZA = Sw*aw + Zeta_e*nu*St*at*(1 - k);
A(3,3) = A(3,3)*(1 - (Delta_ZA/ZA));

%%%%Czq
A(3,4) = A(3,4)*Zeta_e;

%%%%Czdeltae
B(3,1) = B(3,1)*Zeta_e;

%%LATERAL/DIRECTIONAL
%%%%CyB

```

```

A(6,6) = A(6,6)*Zeta_rp;

%%%%Cyp
A(6,7) = A(6,7)*Zeta_rp;

%%%%Cyr
A(6,8) = A(6,8)*Zeta_rp;

%%%%Cydeltaa
B(6,4) = B(6,4)*Zeta_a;

%%%%Cydeltar
B(6,5) = B(6,5)*Zeta_r;

%%%%CydeltaDFTail
B(6,2) = B(6,2)*Zeta_e;

%%%%Clp
A(7,7) = A(7,7)*Zeta_ar;

%%%%Clr
A(7,8) = A(7,8)*Zeta_rp;

%%%%ClB
A(7,6) = A(7,6)*Zeta_rp;

%%%%Cldeltaa
B(7,4) = B(7,4)*Zeta_a;

%%%%Cldeltar
B(7,5) = B(7,5)*Zeta_r;

%%%%CldeltaDFTail
B(7,2) = B(7,2)*Zeta_e;

%%%%CnB
A(8,6) = A(8,6)*Zeta_rp;

%%%%Cnp
A(8,7) = A(8,7)*Zeta_rp;

%%%%Cnr
A(8,8) = A(8,8)*Zeta_rp;

%%%%Cndeltaa

```

```

B(8,4) = B(8,4)*Zeta_a;

%%%%Cndeltar
B(8,5) = B(8,5)*Zeta_r;

%%%%CndeltaDFTail
B(8,2) = B(8,2)*Zeta_e;

%Define Cross Coupling Disturbance Models
Gamma_lat = zeros(4,1);
Gamma_lat(3,1) = (((1-Zeta_e)*Ldelta_a)/(6*Lambda));
Gamma_lat(4,1) = ((Kn*(1-Zeta_e)*Ldelta_a)/(6*Lambda));

Gamma_long = zeros(4,1);
Gamma_long(3,1) = (k2*Zdelta_e)/(Zeta_e*k1);
Gamma_long(4,1) = k2*(Mdelta_e*k1 + Malpha_dot*Zdelta_e)/k1;

Gamma_lat = -MaxELEV*Gamma_lat;
Gamma_long = Trim*Gamma_long;

%STORE NEW PLANTS and Disturbance Inputs
cd /eng1/vcacciat/Thesis/PLANTS/failed_plants
fid = fopen(['mF' num2str(u) 'e.m'],'w');
fprintf(fid,['%%Failure Case #' num2str(u)]);
fprintf(fid,'nZeta_e =%3.2f; Zeta_a =%3.2f;
Zeta_r =%3.2f;',Zeta_e,Zeta_a,Zeta_r);
fprintf(fid,'nU = %f;',U);
fprintf(fid,' qbar = %f;',qbar);
fprintf(fid,['n \nA_VISTA_F = []']);
fprintf(fid,'%f,%f,%f,%f,%f,%f,%f;',A');
fprintf(fid,[' ]; ']);
fprintf(fid,['n \nB_VISTA_F = []']);
fprintf(fid,'%f, %f, %f, %f, %f;',B');
fprintf(fid,[' ]; ']);
fprintf(fid,['n \nGamma_long = []']);
fprintf(fid,'%f;', Gamma_long);
fprintf(fid,[' ]; ']);
fprintf(fid,['n \nGamma_lat = []']);
fprintf(fid,'%f;', Gamma_lat);
fprintf(fid,[' ]; '));
status = fclose(fid);

end

```

Appendix B. Parameter Space Data Points

This appendix contains a list of all of the data points for which LTI aircraft models are generated by the SRF.

| # | U(ft/sec) | Mach | Alt(ft) | Tanks | $\dot{q}(\text{lb}/\text{ft}^2)$ | # | U(ft/sec) | Mach | Alt(ft) | Tanks | $\dot{q}(\text{lb}/\text{ft}^2)$ |
|----|-----------|------|---------|-------|----------------------------------|----|-----------|------|---------|-------|----------------------------------|
| 1 | 356.3108 | 0.38 | 30000 | 3 | 63.6460 | 48 | 258.9626 | 0.24 | 1000 | 0 | 82.2802 |
| 2 | 306.8269 | 0.31 | 20000 | 1 | 65.4696 | 49 | 276.1144 | 0.26 | 5000 | 2 | 83.3181 |
| 3 | 306.8179 | 0.31 | 20000 | 0 | 65.4696 | 50 | 276.8024 | 0.26 | 5000 | 1 | 83.3181 |
| 4 | 282.6290 | 0.28 | 15000 | 1 | 65.5666 | 51 | 275.8478 | 0.26 | 5000 | 3 | 83.3181 |
| 5 | 371.1044 | 0.39 | 30000 | 1 | 67.0399 | 52 | 276.8001 | 0.26 | 5000 | 0 | 83.3181 |
| 6 | 371.0953 | 0.39 | 30000 | 0 | 67.0399 | 53 | 351.7636 | 0.35 | 20000 | 2 | 83.4550 |
| 7 | 340.3061 | 0.35 | 25000 | 1 | 67.4267 | 54 | 352.6862 | 0.35 | 20000 | 1 | 83.4550 |
| 8 | 340.2972 | 0.35 | 25000 | 0 | 67.4267 | 55 | 351.2820 | 0.35 | 20000 | 3 | 83.4550 |
| 9 | 409.8783 | 0.44 | 35000 | 1 | 67.6717 | 56 | 352.6857 | 0.35 | 20000 | 0 | 83.4550 |
| 10 | 407.3858 | 0.44 | 35000 | 3 | 67.6717 | 57 | 384.2509 | 0.39 | 25000 | 2 | 83.7192 |
| 11 | 268.5053 | 0.26 | 10000 | 1 | 68.8746 | 58 | 385.2349 | 0.39 | 25000 | 1 | 83.7192 |
| 12 | 268.4976 | 0.26 | 10000 | 0 | 68.8746 | 59 | 383.6765 | 0.39 | 25000 | 3 | 83.7192 |
| 13 | 233.5497 | 0.22 | 1000 | 3 | 69.1382 | 60 | 385.2340 | 0.39 | 25000 | 0 | 83.7192 |
| 14 | 316.8115 | 0.32 | 20000 | 3 | 69.7616 | 61 | 473.5181 | 0.50 | 35000 | 2 | 87.3860 |
| 15 | 292.9719 | 0.29 | 15000 | 3 | 70.3335 | 62 | 474.5858 | 0.50 | 35000 | 1 | 87.3860 |
| 16 | 252.9760 | 0.24 | 5000 | 1 | 70.9929 | 63 | 472.6632 | 0.50 | 35000 | 3 | 87.3860 |
| 17 | 251.7848 | 0.24 | 5000 | 3 | 70.9929 | 64 | 474.5876 | 0.50 | 35000 | 0 | 87.3860 |
| 18 | 349.9148 | 0.36 | 25000 | 3 | 71.3347 | 65 | 605.7848 | 0.64 | 45000 | 1 | 88.7159 |
| 19 | 279.4878 | 0.27 | 10000 | 2 | 74.2746 | 66 | 605.7899 | 0.64 | 45000 | 0 | 88.7159 |
| 20 | 280.3498 | 0.27 | 10000 | 1 | 74.2746 | 67 | 435.3305 | 0.45 | 30000 | 3 | 89.2543 |
| 21 | 279.1366 | 0.27 | 10000 | 3 | 74.2746 | 68 | 538.1724 | 0.57 | 40000 | 2 | 89.3983 |
| 22 | 280.3444 | 0.27 | 10000 | 0 | 74.2746 | 69 | 539.2541 | 0.57 | 40000 | 1 | 89.3983 |
| 23 | 246.9440 | 0.23 | 1000 | 1 | 75.5664 | 70 | 537.0843 | 0.57 | 40000 | 3 | 89.3983 |
| 24 | 264.9703 | 0.25 | 5000 | 0 | 77.0323 | 71 | 539.2568 | 0.57 | 40000 | 0 | 89.3983 |
| 25 | 442.3595 | 0.47 | 35000 | 0 | 77.2143 | 72 | 314.4668 | 0.30 | 10000 | 2 | 91.6970 |
| 26 | 496.4158 | 0.53 | 40000 | 1 | 77.2914 | 73 | 315.2011 | 0.30 | 10000 | 1 | 91.6970 |
| 27 | 494.0463 | 0.53 | 40000 | 3 | 77.2914 | 74 | 314.1575 | 0.30 | 10000 | 3 | 91.6970 |
| 28 | 496.4142 | 0.53 | 40000 | 0 | 77.2914 | 75 | 315.2010 | 0.30 | 10000 | 0 | 91.6970 |
| 29 | 505.9001 | 0.54 | 40000 | 2 | 80.2356 | 76 | 625.6518 | 0.66 | 45000 | 2 | 94.3473 |
| 30 | 507.2213 | 0.54 | 40000 | 1 | 80.2356 | 77 | 626.6525 | 0.66 | 45000 | 1 | 94.3473 |
| 31 | 504.8485 | 0.54 | 40000 | 3 | 80.2356 | 78 | 626.6591 | 0.66 | 45000 | 0 | 94.3473 |
| 32 | 507.2212 | 0.54 | 40000 | 0 | 80.2356 | 79 | 734.2271 | 0.77 | 50000 | 0 | 101.0962 |
| 33 | 316.8614 | 0.31 | 15000 | 2 | 80.3692 | 80 | 362.6436 | 0.35 | 15000 | 2 | 102.4478 |
| 34 | 317.7535 | 0.31 | 15000 | 1 | 80.3692 | 81 | 363.2888 | 0.35 | 15000 | 1 | 102.4478 |
| 35 | 316.4457 | 0.31 | 15000 | 3 | 80.3692 | 82 | 362.1963 | 0.35 | 15000 | 3 | 102.4478 |
| 36 | 317.7506 | 0.31 | 15000 | 0 | 80.3692 | 83 | 363.2904 | 0.35 | 15000 | 0 | 102.4478 |
| 37 | 451.9645 | 0.48 | 35000 | 2 | 80.5349 | 84 | 655.5445 | 0.69 | 45000 | 3 | 103.1193 |
| 38 | 453.1725 | 0.48 | 35000 | 1 | 80.5349 | 85 | 744.5969 | 0.78 | 50000 | 0 | 103.7392 |
| 39 | 451.1247 | 0.48 | 35000 | 3 | 80.5349 | 86 | 667.0249 | 0.70 | 45000 | 2 | 106.1299 |
| 40 | 453.1725 | 0.48 | 35000 | 0 | 80.5349 | 87 | 667.9643 | 0.70 | 45000 | 1 | 106.1299 |
| 41 | 414.1389 | 0.43 | 30000 | 2 | 81.4969 | 88 | 665.8376 | 0.70 | 45000 | 3 | 106.1299 |
| 42 | 415.2408 | 0.43 | 30000 | 1 | 81.4969 | 89 | 667.9745 | 0.70 | 45000 | 0 | 106.1299 |
| 43 | 413.4491 | 0.43 | 30000 | 3 | 81.4969 | 90 | 754.9666 | 0.79 | 50000 | 0 | 106.4162 |
| 44 | 415.2395 | 0.43 | 30000 | 0 | 81.4969 | 91 | 407.6037 | 0.40 | 20000 | 2 | 109.0025 |
| 45 | 258.3013 | 0.24 | 1000 | 2 | 82.2802 | 92 | 408.2125 | 0.40 | 20000 | 1 | 109.0025 |
| 46 | 258.9648 | 0.24 | 1000 | 1 | 82.2802 | 93 | 407.0826 | 0.40 | 20000 | 3 | 109.0025 |
| 47 | 258.0598 | 0.24 | 1000 | 3 | 82.2802 | 94 | 408.2147 | 0.40 | 20000 | 0 | 109.0025 |

| # | U(ft/sec) | Mach | Alt(ft) | Tanks | $q(\text{lb}/\text{ft}^2)$ |
|-----|-----------|------|---------|-------|----------------------------|
| 95 | 764.1132 | 0.80 | 50000 | 2 | 109.1273 |
| 96 | 765.2863 | 0.80 | 50000 | 1 | 109.1273 |
| 97 | 765.3006 | 0.80 | 50000 | 0 | 109.1273 |
| 98 | 489.3799 | 0.50 | 30000 | 2 | 110.1905 |
| 99 | 490.0036 | 0.50 | 30000 | 1 | 110.1905 |
| 100 | 488.6942 | 0.50 | 30000 | 3 | 110.1905 |
| 101 | 490.0065 | 0.50 | 30000 | 0 | 110.1905 |
| 102 | 323.1903 | 0.30 | 5000 | 2 | 110.9265 |
| 103 | 323.7697 | 0.30 | 5000 | 1 | 110.9265 |
| 104 | 322.7902 | 0.30 | 5000 | 3 | 110.9265 |
| 105 | 323.7712 | 0.30 | 5000 | 0 | 110.9265 |
| 106 | 774.5156 | 0.81 | 50000 | 2 | 111.8726 |
| 107 | 775.6357 | 0.81 | 50000 | 1 | 111.8726 |
| 108 | 775.6498 | 0.81 | 50000 | 0 | 111.8726 |
| 109 | 784.8859 | 0.82 | 50000 | 2 | 114.6519 |
| 110 | 785.9575 | 0.82 | 50000 | 1 | 114.6519 |
| 111 | 785.9714 | 0.82 | 50000 | 0 | 114.6519 |
| 112 | 795.2271 | 0.83 | 50000 | 2 | 117.4653 |
| 113 | 796.2540 | 0.83 | 50000 | 1 | 117.4653 |
| 114 | 796.2675 | 0.83 | 50000 | 0 | 117.4653 |
| 115 | 805.5421 | 0.84 | 50000 | 2 | 120.3129 |
| 116 | 806.5272 | 0.84 | 50000 | 1 | 120.3129 |
| 117 | 803.9543 | 0.84 | 50000 | 3 | 120.3129 |
| 118 | 806.5403 | 0.84 | 50000 | 0 | 120.3129 |
| 119 | 718.4875 | 0.75 | 45000 | 2 | 121.8328 |
| 120 | 719.3352 | 0.75 | 45000 | 1 | 121.8328 |
| 121 | 717.1732 | 0.75 | 45000 | 3 | 121.8328 |
| 122 | 719.3445 | 0.75 | 45000 | 0 | 121.8328 |
| 123 | 815.8332 | 0.85 | 50000 | 2 | 123.1945 |
| 124 | 816.6036 | 0.85 | 50000 | 1 | 123.1945 |
| 125 | 814.2523 | 0.85 | 50000 | 3 | 123.1945 |
| 126 | 816.6129 | 0.85 | 50000 | 0 | 123.1945 |
| 127 | 825.9927 | 0.86 | 50000 | 2 | 126.1103 |
| 128 | 826.6674 | 0.86 | 50000 | 1 | 126.1103 |
| 129 | 824.5324 | 0.86 | 50000 | 3 | 126.1103 |
| 130 | 826.6767 | 0.86 | 50000 | 0 | 126.1103 |
| 131 | 836.0692 | 0.87 | 50000 | 2 | 129.0601 |
| 132 | 836.7357 | 0.87 | 50000 | 1 | 129.0601 |
| 133 | 834.7814 | 0.87 | 50000 | 3 | 129.0601 |
| 134 | 836.7450 | 0.87 | 50000 | 0 | 129.0601 |
| 135 | 330.6034 | 0.30 | 1000 | 2 | 129.4213 |
| 136 | 331.0931 | 0.30 | 1000 | 1 | 129.4213 |
| 137 | 330.2076 | 0.30 | 1000 | 3 | 129.4213 |
| 138 | 331.0943 | 0.30 | 1000 | 0 | 129.4213 |
| 139 | 411.7170 | 0.39 | 15000 | 2 | 129.8252 |
| 140 | 412.2256 | 0.39 | 15000 | 1 | 129.8252 |
| 141 | 411.1960 | 0.39 | 15000 | 3 | 129.8252 |

| # | U(ft/sec) | Mach | Alt(ft) | Tanks | $q(\text{lb}/\text{ft}^2)$ |
|-----|-----------|------|---------|-------|----------------------------|
| 142 | 412.2274 | 0.39 | 15000 | 0 | 129.8252 |
| 143 | 534.4108 | 0.54 | 30000 | 2 | 129.9582 |
| 144 | 534.9595 | 0.54 | 30000 | 1 | 129.9582 |
| 145 | 533.6214 | 0.54 | 30000 | 3 | 129.9582 |
| 146 | 534.9625 | 0.54 | 30000 | 0 | 129.9582 |
| 147 | 488.3471 | 0.49 | 25000 | 2 | 130.0074 |
| 148 | 488.8853 | 0.49 | 25000 | 1 | 130.0074 |
| 149 | 487.6650 | 0.49 | 25000 | 3 | 130.0074 |
| 150 | 488.8876 | 0.49 | 25000 | 0 | 130.0074 |
| 151 | 587.5572 | 0.61 | 35000 | 2 | 130.0653 |
| 152 | 588.1083 | 0.61 | 35000 | 1 | 130.0653 |
| 153 | 586.6335 | 0.61 | 35000 | 3 | 130.0653 |
| 154 | 588.1118 | 0.61 | 35000 | 0 | 130.0653 |
| 155 | 447.9792 | 0.44 | 20000 | 2 | 130.1006 |
| 156 | 448.5037 | 0.44 | 20000 | 1 | 130.1006 |
| 157 | 447.3843 | 0.44 | 20000 | 3 | 130.1006 |
| 158 | 448.5057 | 0.44 | 20000 | 0 | 130.1006 |
| 159 | 749.0121 | 0.78 | 45000 | 2 | 131.7744 |
| 160 | 749.5445 | 0.78 | 45000 | 1 | 131.7744 |
| 161 | 747.7755 | 0.78 | 45000 | 3 | 131.7744 |
| 162 | 749.5507 | 0.78 | 45000 | 0 | 131.7744 |
| 163 | 846.1508 | 0.88 | 50000 | 2 | 132.0441 |
| 164 | 846.8071 | 0.88 | 50000 | 1 | 132.0441 |
| 165 | 844.9784 | 0.88 | 50000 | 3 | 132.0441 |
| 166 | 846.8163 | 0.88 | 50000 | 0 | 132.0441 |
| 167 | 671.9930 | 0.70 | 40000 | 2 | 134.8266 |
| 168 | 672.4916 | 0.70 | 40000 | 1 | 134.8266 |
| 169 | 670.9288 | 0.70 | 40000 | 3 | 134.8266 |
| 170 | 672.4959 | 0.70 | 40000 | 0 | 134.8266 |
| 171 | 856.2359 | 0.89 | 50000 | 2 | 135.0621 |
| 172 | 856.8798 | 0.89 | 50000 | 1 | 135.0621 |
| 173 | 855.0580 | 0.89 | 50000 | 3 | 135.0621 |
| 174 | 856.8889 | 0.89 | 50000 | 0 | 135.0621 |
| 175 | 461.4592 | 0.45 | 20000 | 3 | 137.9562 |
| 176 | 866.3225 | 0.90 | 50000 | 2 | 138.1142 |
| 177 | 866.9518 | 0.90 | 50000 | 1 | 138.1142 |
| 178 | 865.1412 | 0.90 | 50000 | 3 | 138.1142 |
| 179 | 866.9608 | 0.90 | 50000 | 0 | 138.1142 |
| 180 | 592.3990 | 0.60 | 30000 | 3 | 158.6743 |
| 181 | 427.6254 | 0.40 | 10000 | 3 | 163.0169 |
| 182 | 848.8048 | 0.88 | 45000 | 2 | 167.7286 |
| 183 | 849.1861 | 0.88 | 45000 | 1 | 167.7286 |
| 184 | 847.9139 | 0.88 | 45000 | 3 | 167.7286 |
| 185 | 849.1904 | 0.88 | 45000 | 0 | 167.7286 |
| 186 | 515.3699 | 0.50 | 20000 | 2 | 170.3164 |
| 187 | 515.6489 | 0.50 | 20000 | 1 | 170.3164 |
| 188 | 514.9072 | 0.50 | 20000 | 3 | 170.3164 |

| # | U(ft/sec) | Mach | Alt(ft) | Tanks | $\dot{q}(\text{lb}/\text{ft}^2)$ |
|-----|-----------|------|---------|-------|----------------------------------|
| 189 | 515.6502 | 0.50 | 20000 | 0 | 170.3164 |
| 190 | 643.1663 | 0.65 | 30000 | 3 | 186.2219 |
| 191 | 567.6104 | 0.55 | 20000 | 3 | 206.0828 |
| 192 | 482.4902 | 0.45 | 10000 | 3 | 206.3182 |
| 193 | 840.2690 | 0.87 | 40000 | 2 | 208.2658 |
| 194 | 840.5090 | 0.87 | 40000 | 1 | 208.2658 |
| 195 | 839.7098 | 0.87 | 40000 | 3 | 208.2658 |
| 196 | 840.5118 | 0.87 | 40000 | 0 | 208.2658 |
| 197 | 694.1871 | 0.70 | 30000 | 2 | 215.9733 |
| 198 | 694.4091 | 0.70 | 30000 | 1 | 215.9733 |
| 199 | 693.6675 | 0.70 | 30000 | 3 | 215.9733 |
| 200 | 694.4109 | 0.70 | 30000 | 0 | 215.9733 |
| 201 | 869.9337 | 0.90 | 40000 | 1 | 222.8766 |
| 202 | 869.2272 | 0.90 | 40000 | 3 | 222.8766 |
| 203 | 869.9363 | 0.90 | 40000 | 0 | 222.8766 |
| 204 | 443.5660 | 0.40 | 1000 | 2 | 228.5562 |
| 205 | 443.7502 | 0.40 | 1000 | 1 | 228.5562 |
| 206 | 443.2620 | 0.40 | 1000 | 3 | 228.5562 |
| 207 | 443.7508 | 0.40 | 1000 | 0 | 228.5562 |
| 208 | 620.0384 | 0.60 | 20000 | 3 | 245.2556 |
| 209 | 743.9712 | 0.75 | 30000 | 3 | 247.9286 |
| 210 | 537.3339 | 0.50 | 10000 | 2 | 254.7139 |
| 211 | 537.4980 | 0.50 | 10000 | 1 | 254.7139 |
| 212 | 536.9779 | 0.50 | 10000 | 3 | 254.7139 |
| 213 | 537.4987 | 0.50 | 10000 | 0 | 254.7139 |
| 214 | 845.4997 | 0.87 | 35000 | 2 | 264.5698 |
| 215 | 845.6716 | 0.87 | 35000 | 1 | 264.5698 |
| 216 | 845.0479 | 0.87 | 35000 | 3 | 264.5698 |
| 217 | 845.6735 | 0.87 | 35000 | 0 | 264.5698 |
| 218 | 794.1589 | 0.80 | 30000 | 3 | 282.0876 |
| 219 | 672.3800 | 0.65 | 20000 | 3 | 287.8346 |
| 220 | 591.2659 | 0.55 | 10000 | 3 | 308.2038 |
| 221 | 864.8840 | 0.87 | 30000 | 2 | 333.6127 |
| 222 | 865.0098 | 0.87 | 30000 | 1 | 333.6127 |
| 223 | 864.5085 | 0.87 | 30000 | 3 | 333.6127 |
| 224 | 865.0110 | 0.87 | 30000 | 0 | 333.6127 |
| 225 | 724.9935 | 0.70 | 20000 | 2 | 333.8201 |
| 226 | 725.1219 | 0.70 | 20000 | 1 | 333.8201 |
| 227 | 724.5963 | 0.70 | 20000 | 3 | 333.8201 |
| 228 | 725.1229 | 0.70 | 20000 | 0 | 333.8201 |
| 229 | 894.9976 | 0.90 | 30000 | 1 | 357.0172 |
| 230 | 894.5495 | 0.90 | 30000 | 3 | 357.0172 |
| 231 | 894.9987 | 0.90 | 30000 | 0 | 357.0172 |
| 232 | 645.4193 | 0.60 | 10000 | 3 | 366.7880 |
| 233 | 776.7334 | 0.75 | 20000 | 3 | 383.2118 |
| 234 | 883.6877 | 0.87 | 25000 | 2 | 416.6143 |
| 235 | 883.7897 | 0.87 | 25000 | 1 | 416.6143 |

| # | U(ft/sec) | Mach | Alt(ft) | Tanks | $\dot{q}(\text{lb}/\text{ft}^2)$ |
|-----|-----------|------|---------|-------|----------------------------------|
| 236 | 883.3687 | 0.87 | 25000 | 3 | 416.6143 |
| 237 | 883.7905 | 0.87 | 25000 | 0 | 416.6143 |
| 238 | 699.5460 | 0.65 | 10000 | 3 | 430.4664 |
| 239 | 828.8166 | 0.80 | 20000 | 3 | 436.0099 |
| 240 | 753.9324 | 0.70 | 10000 | 2 | 499.2391 |
| 241 | 754.0159 | 0.70 | 10000 | 1 | 499.2391 |
| 242 | 753.6174 | 0.70 | 10000 | 3 | 499.2391 |
| 243 | 754.0165 | 0.70 | 10000 | 0 | 499.2391 |
| 244 | 891.6245 | 0.86 | 20000 | 2 | 503.8640 |
| 245 | 891.7075 | 0.86 | 20000 | 1 | 503.8640 |
| 246 | 891.3319 | 0.86 | 20000 | 3 | 503.8640 |
| 247 | 891.7080 | 0.86 | 20000 | 0 | 503.8640 |
| 248 | 667.3123 | 0.60 | 1000 | 2 | 514.2514 |
| 249 | 667.3877 | 0.60 | 1000 | 1 | 514.2514 |
| 250 | 667.0334 | 0.60 | 1000 | 3 | 514.2514 |
| 251 | 667.3881 | 0.60 | 1000 | 0 | 514.2514 |
| 252 | 933.2764 | 0.90 | 20000 | 1 | 551.8250 |
| 253 | 932.9374 | 0.90 | 20000 | 3 | 551.8250 |
| 254 | 933.2769 | 0.90 | 20000 | 0 | 551.8250 |
| 255 | 807.6479 | 0.75 | 10000 | 3 | 573.1062 |
| 256 | 909.3434 | 0.86 | 15000 | 2 | 618.5337 |
| 257 | 909.4110 | 0.86 | 15000 | 1 | 618.5337 |
| 258 | 909.0850 | 0.86 | 15000 | 3 | 618.5337 |
| 259 | 909.4115 | 0.86 | 15000 | 0 | 618.5337 |
| 260 | 861.6325 | 0.80 | 10000 | 3 | 652.0676 |
| 261 | 778.8329 | 0.70 | 1000 | 2 | 699.9532 |
| 262 | 778.8885 | 0.70 | 1000 | 1 | 699.9532 |
| 263 | 778.5750 | 0.70 | 1000 | 3 | 699.9532 |
| 264 | 778.8887 | 0.70 | 1000 | 0 | 699.9532 |
| 265 | 937.4568 | 0.87 | 10000 | 2 | 771.1717 |
| 266 | 937.5140 | 0.87 | 10000 | 1 | 771.1717 |
| 267 | 937.2269 | 0.87 | 10000 | 3 | 771.1717 |
| 268 | 937.5142 | 0.87 | 10000 | 0 | 771.1717 |
| 269 | 969.8751 | 0.90 | 10000 | 1 | 825.2729 |
| 270 | 969.6061 | 0.90 | 10000 | 3 | 825.2729 |
| 271 | 969.8754 | 0.90 | 10000 | 0 | 825.2729 |
| 272 | 965.6384 | 0.88 | 5000 | 2 | 954.4603 |
| 273 | 965.6884 | 0.88 | 5000 | 1 | 954.4603 |
| 274 | 965.4279 | 0.88 | 5000 | 3 | 954.4603 |
| 275 | 965.6886 | 0.88 | 5000 | 0 | 954.4603 |
| 276 | 979.3263 | 0.88 | 1000 | 2 | 1106.2120 |
| 277 | 979.3723 | 0.88 | 1000 | 1 | 1106.2120 |
| 278 | 979.1241 | 0.88 | 1000 | 3 | 1106.2120 |
| 279 | 979.3725 | 0.88 | 1000 | 0 | 1106.2120 |
| 280 | 1001.6410 | 0.90 | 1000 | 1 | 1157.0650 |
| 281 | 1001.4010 | 0.90 | 1000 | 3 | 1157.0650 |
| 282 | 1001.6410 | 0.90 | 1000 | 0 | 1157.0650 |

Appendix C. Longitudinal Channel Time Response

| Variable | Units |
|-----------------------|-------------|
| \bar{q} | lbs/ ft^2 |
| t_1 | seconds |
| Δ_t | seconds |
| δ_{elev} | deg/sec |
| $\dot{\delta}_{elev}$ | degrees |
| g_{pil} | g's |
| α | degrees |

C.1 Longitudinal Unit C_{cmd} Step Input Time Response (Healthy)

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δt | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil(ss)}$ | α_{ss} |
|----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------------|----------------------|---------------|---------------|
| 1 | 119 | 65.4696 | 0.048 | 0.029 | 0.980 | 1.630 | 5.215 | 0.000 | 7.388 | 0.462 | 2.196 | 20.240 |
| 2 | 253 | 65.4696 | 0.087 | 0.029 | 1.102 | 1.630 | 5.215 | 0.848 | 7.407 | 0.353 | 2.196 | 20.249 |
| 3 | 118 | 65.5666 | 0.048 | 0.032 | 0.985 | 1.769 | 5.661 | 0.000 | 7.388 | 0.494 | 2.182 | 20.037 |
| 4 | 122 | 67.0399 | 0.087 | 0.024 | 1.083 | 1.347 | 4.311 | 0.425 | 7.407 | 0.492 | 2.234 | 20.316 |
| 5 | 256 | 67.0399 | 0.086 | 0.024 | 1.083 | 1.347 | 4.312 | 0.846 | 7.406 | 0.229 | 2.234 | 20.319 |
| 6 | 121 | 67.4267 | 0.087 | 0.026 | 1.091 | 1.469 | 4.702 | 0.576 | 7.407 | 0.528 | 2.217 | 20.010 |
| 7 | 255 | 67.4267 | 0.086 | 0.026 | 1.090 | 1.469 | 4.702 | 1.219 | 7.407 | 0.264 | 2.217 | 20.014 |
| 8 | 124 | 67.6717 | 0.086 | 0.022 | 1.075 | 1.220 | 3.904 | 0.754 | 7.406 | 0.429 | 2.255 | 20.435 |
| 9 | 116 | 68.8746 | 0.084 | 0.034 | 1.117 | 1.862 | 5.959 | 2.449 | 7.407 | 0.554 | 2.177 | 19.117 |
| 10 | 251 | 68.8746 | 0.083 | 0.034 | 1.116 | 1.862 | 5.959 | 0.000 | 7.407 | 0.292 | 2.177 | 19.123 |
| 11 | 115 | 70.9929 | 0.082 | 0.036 | 1.123 | 1.976 | 6.325 | 0.000 | 7.406 | 0.502 | 2.169 | 18.507 |
| 12 | 10 | 74.2746 | 0.075 | 0.032 | 1.100 | 1.789 | 5.725 | 0.000 | 7.403 | -1.334 | 2.188 | 18.716 |
| 13 | 66 | 74.2746 | 0.080 | 0.032 | 1.108 | 1.783 | 5.707 | 3.376 | 7.405 | 0.323 | 2.189 | 18.039 |
| 14 | 202 | 74.2746 | 0.079 | 0.032 | 1.108 | 1.784 | 5.707 | 0.000 | 7.405 | 0.079 | 2.189 | 18.044 |
| 15 | 113 | 75.5664 | 0.078 | 0.036 | 1.126 | 2.025 | 6.479 | 0.000 | 7.405 | 0.349 | 2.169 | 17.501 |
| 16 | 250 | 77.0323 | 0.077 | 0.034 | 1.114 | 1.887 | 6.038 | 0.000 | 7.404 | 0.028 | 2.181 | 17.379 |
| 17 | 258 | 77.2143 | 0.081 | 0.020 | 1.044 | 1.130 | 3.617 | 0.000 | 7.402 | 0.153 | 2.286 | 18.694 |
| 18 | 125 | 77.2914 | 0.081 | 0.018 | 1.039 | 1.007 | 3.223 | 0.000 | 7.402 | 0.390 | 2.311 | 19.068 |
| 19 | 259 | 77.2914 | 0.080 | 0.018 | 1.039 | 1.007 | 3.223 | 0.000 | 7.401 | 0.164 | 2.311 | 19.064 |
| 20 | 37 | 80.2356 | 0.076 | 0.018 | 1.036 | 0.988 | 3.163 | 0.000 | 7.400 | -0.359 | 2.319 | 19.092 |
| 21 | 93 | 80.2356 | 0.077 | 0.018 | 1.033 | 0.986 | 3.154 | 0.000 | 7.400 | 0.399 | 2.321 | 18.460 |
| 22 | 229 | 80.2356 | 0.076 | 0.018 | 1.033 | 0.986 | 3.154 | 0.000 | 7.400 | 0.184 | 2.321 | 18.455 |
| 23 | 15 | 80.3692 | 0.077 | 0.028 | 1.059 | 1.578 | 5.050 | 0.000 | 7.401 | -1.054 | 2.218 | 17.693 |
| 24 | 71 | 80.3692 | 0.081 | 0.028 | 1.058 | 1.574 | 5.035 | 0.000 | 7.402 | 0.365 | 2.219 | 17.017 |
| 25 | 207 | 80.3692 | 0.080 | 0.028 | 1.059 | 1.574 | 5.035 | 0.000 | 7.402 | 0.142 | 2.219 | 17.020 |
| 26 | 33 | 80.5349 | 0.076 | 0.020 | 1.040 | 1.106 | 3.540 | 0.000 | 7.400 | -0.592 | 2.294 | 18.686 |
| 27 | 89 | 80.5349 | 0.078 | 0.020 | 1.037 | 1.103 | 3.531 | 0.000 | 7.400 | 0.341 | 2.296 | 18.036 |
| 28 | 225 | 80.5349 | 0.077 | 0.020 | 1.037 | 1.103 | 3.531 | 0.000 | 7.400 | 0.125 | 2.296 | 18.034 |
| 29 | 28 | 81.4969 | 0.075 | 0.022 | 1.042 | 1.207 | 3.863 | 0.000 | 7.400 | -0.759 | 2.276 | 18.219 |
| 30 | 84 | 81.4969 | 0.078 | 0.022 | 1.040 | 1.204 | 3.853 | 0.000 | 7.400 | 0.303 | 2.277 | 17.567 |
| 31 | 220 | 81.4969 | 0.077 | 0.022 | 1.040 | 1.204 | 3.853 | 0.000 | 7.400 | 0.087 | 2.277 | 17.566 |
| 32 | 1 | 82.2802 | 0.075 | 0.035 | 1.068 | 1.936 | 6.194 | 0.000 | 7.401 | -1.642 | 2.182 | 16.987 |
| 33 | 57 | 82.2802 | 0.080 | 0.035 | 1.067 | 1.931 | 6.178 | 0.000 | 7.402 | -0.157 | 2.182 | 16.355 |
| 34 | 193 | 82.2802 | 0.079 | 0.035 | 1.068 | 1.931 | 6.178 | 0.000 | 7.402 | -0.377 | 2.182 | 16.359 |
| 35 | 7 | 83.3181 | 0.075 | 0.033 | 1.059 | 1.811 | 5.795 | 0.000 | 7.400 | -1.666 | 2.194 | 16.974 |
| 36 | 63 | 83.3181 | 0.080 | 0.033 | 1.057 | 1.806 | 5.780 | 0.000 | 7.401 | -0.255 | 2.195 | 16.352 |
| 37 | 199 | 83.3181 | 0.078 | 0.033 | 1.059 | 1.806 | 5.780 | 0.000 | 7.401 | -0.471 | 2.195 | 16.356 |
| 38 | 19 | 83.4550 | 0.074 | 0.026 | 1.048 | 1.421 | 4.549 | 0.000 | 7.399 | -1.027 | 2.242 | 17.376 |
| 39 | 75 | 83.4550 | 0.077 | 0.026 | 1.048 | 1.418 | 4.537 | 0.000 | 7.400 | 0.250 | 2.243 | 16.718 |
| 40 | 211 | 83.4550 | 0.076 | 0.026 | 1.048 | 1.418 | 4.537 | 0.000 | 7.400 | 0.038 | 2.243 | 16.719 |

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δt | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\delta_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil(ss)}$ | α_{ss} |
|----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------|----------------------|---------------|---------------|
| 42 | 81 | 83.7192 | 0.076 | 0.023 | 1.041 | 1.298 | 4.153 | 0.000 | 7.400 | 0.258 | 2.263 | 16.914 |
| 43 | 217 | 83.7192 | 0.075 | 0.023 | 1.042 | 1.298 | 4.153 | 0.000 | 7.399 | 0.048 | 2.263 | 16.914 |
| 44 | 34 | 87.3860 | 0.069 | 0.019 | 1.026 | 1.056 | 3.379 | 0.000 | 7.396 | -0.468 | 2.315 | 17.410 |
| 45 | 90 | 87.3860 | 0.070 | 0.019 | 1.024 | 1.054 | 3.371 | 0.000 | 7.397 | 0.335 | 2.317 | 16.802 |
| 46 | 226 | 87.3860 | 0.069 | 0.019 | 1.024 | 1.054 | 3.371 | 0.000 | 7.396 | 0.139 | 2.317 | 16.799 |
| 47 | 127 | 88.7159 | 0.071 | 0.015 | 0.967 | 0.825 | 2.641 | 0.000 | 7.393 | 0.392 | 2.397 | 16.771 |
| 48 | 261 | 88.7159 | 0.070 | 0.015 | 0.968 | 0.825 | 2.641 | 0.000 | 7.393 | 0.209 | 2.397 | 16.764 |
| 49 | 38 | 89.3983 | 0.067 | 0.017 | 1.016 | 0.929 | 2.973 | 0.000 | 7.395 | -0.106 | 2.349 | 17.357 |
| 50 | 94 | 89.3983 | 0.076 | 0.017 | 0.973 | 0.927 | 2.967 | 0.000 | 7.395 | 0.411 | 2.363 | 16.532 |
| 51 | 230 | 89.3983 | 0.075 | 0.017 | 0.974 | 0.927 | 2.967 | 0.000 | 7.394 | 0.222 | 2.363 | 16.527 |
| 52 | 11 | 91.6970 | 0.068 | 0.029 | 1.038 | 1.590 | 5.088 | 0.000 | 7.395 | -2.047 | 2.227 | 16.011 |
| 53 | 67 | 91.6970 | 0.071 | 0.029 | 1.039 | 1.586 | 5.076 | 0.000 | 7.397 | -0.707 | 2.227 | 15.385 |
| 54 | 203 | 91.6970 | 0.070 | 0.029 | 1.040 | 1.586 | 5.076 | 0.000 | 7.396 | -0.900 | 2.227 | 15.386 |
| 55 | 41 | 94.3473 | 0.064 | 0.014 | 0.958 | 0.799 | 2.557 | 0.000 | 7.389 | -0.229 | 2.415 | 16.398 |
| 56 | 97 | 94.3473 | 0.065 | 0.014 | 0.955 | 0.798 | 2.553 | 0.000 | 7.389 | 0.188 | 2.417 | 15.877 |
| 57 | 233 | 94.3473 | 0.064 | 0.014 | 0.956 | 0.798 | 2.553 | 0.000 | 7.389 | 0.020 | 2.417 | 15.870 |
| 58 | 262 | 101.0962 | 0.050 | 0.012 | 0.934 | 0.681 | 2.179 | 0.000 | 7.379 | -0.085 | 2.477 | 14.955 |
| 59 | 16 | 102.4478 | 0.061 | 0.025 | 1.005 | 1.379 | 4.412 | 0.000 | 7.390 | -1.262 | 2.269 | 14.491 |
| 60 | 72 | 102.4478 | 0.065 | 0.025 | 1.001 | 1.376 | 4.404 | 0.000 | 7.391 | -0.227 | 2.269 | 13.908 |
| 61 | 208 | 102.4478 | 0.064 | 0.025 | 1.002 | 1.376 | 4.404 | 0.000 | 7.391 | -0.395 | 2.269 | 13.907 |
| 62 | 263 | 103.7392 | 0.050 | 0.012 | 0.920 | 0.672 | 2.149 | 0.000 | 7.377 | -0.146 | 2.484 | 15.343 |
| 63 | 42 | 106.1299 | 0.053 | 0.013 | 0.934 | 0.750 | 2.399 | 0.000 | 7.380 | -0.567 | 2.455 | 14.795 |
| 64 | 98 | 106.1299 | 0.054 | 0.013 | 0.935 | 0.749 | 2.395 | 0.000 | 7.381 | -0.109 | 2.451 | 14.922 |
| 65 | 234 | 106.1299 | 0.053 | 0.013 | 0.935 | 0.749 | 2.395 | 0.000 | 7.380 | -0.252 | 2.451 | 14.910 |
| 66 | 264 | 106.4162 | 0.047 | 0.012 | 0.908 | 0.662 | 2.119 | 0.000 | 7.375 | -0.214 | 2.494 | 14.955 |
| 67 | 20 | 109.0025 | 0.058 | 0.022 | 0.983 | 1.227 | 3.925 | 0.000 | 7.386 | -1.227 | 2.305 | 13.842 |
| 68 | 76 | 109.0025 | 0.061 | 0.022 | 0.980 | 1.225 | 3.920 | 0.000 | 7.387 | -0.393 | 2.306 | 13.308 |
| 69 | 212 | 109.0025 | 0.060 | 0.022 | 0.981 | 1.225 | 3.920 | 0.000 | 7.387 | -0.547 | 2.306 | 13.306 |
| 70 | 46 | 109.1273 | 0.047 | 0.012 | 0.892 | 0.654 | 2.094 | 0.000 | 7.372 | -0.695 | 2.496 | 15.232 |
| 71 | 102 | 109.1273 | 0.047 | 0.012 | 0.893 | 0.653 | 2.091 | 0.000 | 7.373 | -0.149 | 2.504 | 14.592 |
| 72 | 238 | 109.1273 | 0.047 | 0.012 | 0.889 | 0.653 | 2.091 | 0.000 | 7.372 | -0.278 | 2.503 | 14.575 |
| 73 | 29 | 110.1905 | 0.059 | 0.018 | 0.960 | 1.022 | 3.269 | 0.000 | 7.385 | -0.890 | 2.359 | 13.952 |
| 74 | 85 | 110.1905 | 0.060 | 0.018 | 0.957 | 1.020 | 3.265 | 0.000 | 7.385 | -0.360 | 2.360 | 13.471 |
| 75 | 221 | 110.1905 | 0.059 | 0.018 | 0.958 | 1.020 | 3.265 | 0.000 | 7.385 | -0.511 | 2.360 | 13.468 |
| 76 | 8 | 110.9265 | 0.055 | 0.028 | 1.013 | 1.547 | 4.951 | 0.000 | 7.386 | -2.218 | 2.249 | 13.553 |
| 77 | 64 | 110.9265 | 0.058 | 0.028 | 1.012 | 1.544 | 4.942 | 0.000 | 7.388 | -0.986 | 2.250 | 12.936 |
| 78 | 200 | 110.9265 | 0.057 | 0.028 | 1.013 | 1.544 | 4.942 | 0.000 | 7.388 | -1.141 | 2.250 | 12.934 |
| 79 | 47 | 111.8726 | 0.046 | 0.012 | 0.876 | 0.646 | 2.066 | 0.000 | 7.370 | -0.960 | 2.504 | 14.783 |
| 80 | 103 | 111.8726 | 0.046 | 0.012 | 0.874 | 0.645 | 2.063 | 0.000 | 7.370 | -0.426 | 2.512 | 14.159 |
| 81 | 239 | 111.8726 | 0.046 | 0.012 | 0.870 | 0.645 | 2.063 | 0.000 | 7.370 | -0.549 | 2.511 | 14.142 |
| 82 | 48 | 114.6519 | 0.046 | 0.011 | 0.858 | 0.637 | 2.039 | 0.000 | 7.368 | -1.189 | 2.512 | 14.348 |

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δ_t | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\delta_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil(ss)}$ | α_{ss} |
|-----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------|----------------------|---------------|---------------|
| 83 | 104 | 114.6519 | 0.046 | 0.011 | 0.854 | 0.636 | 2.036 | 0.000 | 7.367 | -0.667 | 2.520 | 13.737 |
| 84 | 240 | 114.6519 | 0.046 | 0.011 | 0.850 | 0.636 | 2.036 | 0.000 | 7.367 | -0.785 | 2.519 | 13.719 |
| 85 | 49 | 117.4653 | 0.046 | 0.011 | 0.839 | 0.629 | 2.012 | 0.000 | 7.365 | -1.384 | 2.520 | 13.924 |
| 86 | 105 | 117.4653 | 0.046 | 0.011 | 0.834 | 0.628 | 2.009 | 0.000 | 7.365 | -0.876 | 2.527 | 13.324 |
| 87 | 241 | 117.4653 | 0.046 | 0.011 | 0.830 | 0.628 | 2.009 | 0.000 | 7.364 | -0.989 | 2.527 | 13.307 |
| 88 | 50 | 120.3129 | 0.046 | 0.011 | 0.820 | 0.621 | 1.986 | 0.000 | 7.362 | -1.549 | 2.528 | 13.511 |
| 89 | 106 | 120.3129 | 0.046 | 0.011 | 0.813 | 0.620 | 1.984 | 0.000 | 7.362 | -1.056 | 2.535 | 12.921 |
| 90 | 242 | 120.3129 | 0.046 | 0.011 | 0.810 | 0.620 | 1.984 | 0.000 | 7.361 | -1.164 | 2.535 | 12.903 |
| 91 | 43 | 121.8328 | 0.046 | 0.013 | 0.868 | 0.696 | 2.227 | 0.000 | 7.368 | -0.834 | 2.498 | 13.591 |
| 92 | 99 | 121.8328 | 0.046 | 0.013 | 0.869 | 0.695 | 2.224 | 0.000 | 7.369 | -0.426 | 2.502 | 13.021 |
| 93 | 235 | 121.8328 | 0.046 | 0.013 | 0.865 | 0.695 | 2.224 | 0.000 | 7.368 | -0.543 | 2.502 | 13.009 |
| 94 | 51 | 123.1945 | 0.045 | 0.011 | 0.802 | 0.613 | 1.961 | 0.000 | 7.359 | -1.688 | 2.536 | 13.108 |
| 95 | 107 | 123.1945 | 0.045 | 0.011 | 0.790 | 0.612 | 1.959 | 0.000 | 7.359 | -1.236 | 2.564 | 11.570 |
| 96 | 243 | 123.1945 | 0.045 | 0.011 | 0.787 | 0.612 | 1.959 | 0.000 | 7.358 | -1.341 | 2.564 | 11.561 |
| 97 | 52 | 126.1103 | 0.045 | 0.011 | 0.780 | 0.605 | 1.937 | 0.000 | 7.356 | -1.807 | 2.570 | 11.816 |
| 98 | 108 | 126.1103 | 0.045 | 0.011 | 0.775 | 0.605 | 1.935 | 0.000 | 7.356 | -1.420 | 2.573 | 11.344 |
| 99 | 244 | 126.1103 | 0.045 | 0.011 | 0.772 | 0.605 | 1.935 | 0.000 | 7.356 | -1.521 | 2.573 | 11.334 |
| 100 | 53 | 129.0601 | 0.045 | 0.011 | 0.766 | 0.598 | 1.914 | 0.000 | 7.353 | -1.967 | 2.579 | 11.589 |
| 101 | 109 | 129.0601 | 0.045 | 0.011 | 0.761 | 0.598 | 1.912 | 0.000 | 7.353 | -1.606 | 2.582 | 11.110 |
| 102 | 245 | 129.0601 | 0.045 | 0.011 | 0.758 | 0.598 | 1.912 | 0.000 | 7.353 | -1.704 | 2.581 | 11.100 |
| 103 | 2 | 129.4213 | 0.046 | 0.027 | 0.988 | 1.512 | 4.840 | 0.000 | 7.379 | -2.247 | 2.270 | 11.849 |
| 104 | 58 | 129.4213 | 0.049 | 0.027 | 1.008 | 1.510 | 4.832 | 0.000 | 7.381 | -1.082 | 2.270 | 11.280 |
| 105 | 194 | 129.4213 | 0.046 | 0.027 | 1.007 | 1.510 | 4.832 | 0.000 | 7.381 | -1.214 | 2.270 | 11.277 |
| 106 | 17 | 129.8252 | 0.046 | 0.022 | 0.970 | 1.214 | 3.886 | 0.000 | 7.378 | -1.490 | 2.327 | 12.019 |
| 107 | 73 | 129.8252 | 0.050 | 0.022 | 0.978 | 1.213 | 3.881 | 0.000 | 7.380 | -0.686 | 2.328 | 11.501 |
| 108 | 209 | 129.8252 | 0.049 | 0.022 | 0.979 | 1.213 | 3.881 | 0.000 | 7.379 | -0.816 | 2.328 | 11.497 |
| 109 | 30 | 129.9582 | 0.046 | 0.017 | 0.949 | 0.936 | 2.994 | 0.000 | 7.376 | -0.940 | 2.407 | 12.389 |
| 110 | 86 | 129.9582 | 0.049 | 0.017 | 0.950 | 0.935 | 2.991 | 0.000 | 7.377 | -0.559 | 2.408 | 11.925 |
| 111 | 222 | 129.9582 | 0.047 | 0.017 | 0.948 | 0.935 | 2.991 | 0.000 | 7.377 | -0.684 | 2.408 | 11.920 |
| 112 | 26 | 130.0074 | 0.046 | 0.018 | 0.956 | 1.024 | 3.276 | 0.000 | 7.377 | -1.162 | 2.378 | 12.257 |
| 113 | 82 | 130.0074 | 0.049 | 0.018 | 0.960 | 1.023 | 3.273 | 0.000 | 7.378 | -0.621 | 2.379 | 11.773 |
| 114 | 218 | 130.0074 | 0.048 | 0.018 | 0.960 | 1.023 | 3.273 | 0.000 | 7.378 | -0.749 | 2.379 | 11.769 |
| 115 | 35 | 130.0653 | 0.046 | 0.015 | 0.934 | 0.851 | 2.723 | 0.000 | 7.375 | -0.727 | 2.439 | 12.506 |
| 116 | 91 | 130.0653 | 0.046 | 0.015 | 0.935 | 0.850 | 2.721 | 0.000 | 7.375 | -0.485 | 2.440 | 12.064 |
| 117 | 227 | 130.0653 | 0.046 | 0.015 | 0.931 | 0.850 | 2.721 | 0.000 | 7.375 | -0.608 | 2.440 | 12.058 |
| 118 | 21 | 130.1006 | 0.046 | 0.020 | 0.963 | 1.116 | 3.572 | 0.000 | 7.377 | -1.344 | 2.352 | 12.119 |
| 119 | 77 | 130.1006 | 0.049 | 0.020 | 0.969 | 1.115 | 3.567 | 0.000 | 7.379 | -0.664 | 2.353 | 11.616 |
| 120 | 213 | 130.1006 | 0.049 | 0.020 | 0.969 | 1.115 | 3.567 | 0.000 | 7.379 | -0.792 | 2.353 | 11.612 |
| 121 | 44 | 131.7744 | 0.045 | 0.012 | 0.811 | 0.668 | 2.136 | 0.000 | 7.360 | -0.934 | 2.538 | 11.208 |
| 122 | 100 | 131.7744 | 0.045 | 0.012 | 0.812 | 0.667 | 2.135 | 0.000 | 7.361 | -0.579 | 2.539 | 10.793 |
| 123 | 236 | 131.7744 | 0.045 | 0.012 | 0.809 | 0.667 | 2.135 | 0.000 | 7.360 | -0.683 | 2.539 | 10.786 |

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δ_t | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil(ss)}$ | α_{ss} |
|-----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------------|----------------------|---------------|---------------|
| 124 | 54 | 132.0441 | 0.045 | 0.011 | 0.753 | 0.591 | 1.891 | 0.000 | 7.351 | -2.131 | 2.588 | 11.353 |
| 125 | 110 | 132.0441 | 0.045 | 0.011 | 0.747 | 0.590 | 1.889 | 0.000 | 7.351 | -1.796 | 2.590 | 10.866 |
| 126 | 246 | 132.0441 | 0.045 | 0.011 | 0.744 | 0.590 | 1.889 | 0.000 | 7.350 | -1.891 | 2.590 | 10.856 |
| 127 | 39 | 134.8266 | 0.046 | 0.013 | 0.858 | 0.744 | 2.381 | 0.000 | 7.365 | -0.901 | 2.492 | 12.204 |
| 128 | 95 | 134.8266 | 0.046 | 0.013 | 0.853 | 0.744 | 2.379 | 0.000 | 7.366 | -0.611 | 2.498 | 10.630 |
| 129 | 231 | 134.8266 | 0.046 | 0.013 | 0.849 | 0.743 | 2.379 | 0.000 | 7.366 | -0.719 | 2.498 | 10.626 |
| 130 | 55 | 135.0621 | 0.045 | 0.011 | 0.740 | 0.584 | 1.869 | 0.000 | 7.348 | -2.298 | 2.596 | 11.107 |
| 131 | 111 | 135.0621 | 0.045 | 0.011 | 0.735 | 0.584 | 1.867 | 0.000 | 7.348 | -1.989 | 2.599 | 10.613 |
| 132 | 247 | 135.0621 | 0.045 | 0.011 | 0.732 | 0.584 | 1.867 | 0.000 | 7.347 | -2.081 | 2.599 | 10.603 |
| 133 | 56 | 138.1142 | 0.044 | 0.010 | 0.729 | 0.577 | 1.847 | 0.000 | 7.345 | -2.469 | 2.605 | 10.853 |
| 134 | 112 | 138.1142 | 0.044 | 0.010 | 0.724 | 0.577 | 1.846 | 0.000 | 7.345 | -2.184 | 2.607 | 10.351 |
| 135 | 248 | 138.1142 | 0.044 | 0.010 | 0.721 | 0.577 | 1.846 | 0.000 | 7.344 | -2.274 | 2.607 | 10.341 |
| 136 | 45 | 167.7286 | 0.043 | 0.011 | 0.684 | 0.589 | 1.885 | 0.000 | 7.330 | -2.447 | 2.626 | 8.977 |
| 137 | 101 | 167.7286 | 0.043 | 0.011 | 0.687 | 0.589 | 1.884 | 0.000 | 7.330 | -2.212 | 2.625 | 7.767 |
| 138 | 237 | 167.7286 | 0.043 | 0.011 | 0.684 | 0.589 | 1.884 | 0.000 | 7.330 | -2.284 | 2.625 | 7.761 |
| 139 | 22 | 170.3164 | 0.045 | 0.017 | 0.859 | 0.970 | 3.105 | 0.000 | 7.361 | -1.465 | 2.434 | 9.053 |
| 140 | 78 | 170.3164 | 0.045 | 0.017 | 0.864 | 0.970 | 3.103 | 0.000 | 7.362 | -1.085 | 2.435 | 8.715 |
| 141 | 214 | 170.3164 | 0.045 | 0.017 | 0.860 | 0.970 | 3.103 | 0.000 | 7.362 | -1.179 | 2.435 | 8.713 |
| 142 | 40 | 208.2658 | 0.041 | 0.011 | 0.645 | 0.595 | 1.904 | 0.000 | 7.309 | -2.190 | 2.652 | 6.819 |
| 143 | 96 | 208.2658 | 0.042 | 0.011 | 0.647 | 0.595 | 1.904 | 0.000 | 7.311 | -1.979 | 2.653 | 6.521 |
| 144 | 232 | 208.2658 | 0.041 | 0.011 | 0.645 | 0.595 | 1.904 | 0.000 | 7.310 | -2.037 | 2.653 | 6.517 |
| 145 | 31 | 215.9733 | 0.042 | 0.013 | 0.715 | 0.720 | 2.305 | 0.000 | 7.327 | -1.460 | 2.581 | 7.462 |
| 146 | 87 | 215.9733 | 0.042 | 0.013 | 0.717 | 0.720 | 2.304 | 0.000 | 7.329 | -1.290 | 2.581 | 7.179 |
| 147 | 223 | 215.9733 | 0.042 | 0.013 | 0.714 | 0.720 | 2.304 | 0.000 | 7.328 | -1.354 | 2.581 | 7.176 |
| 148 | 126 | 222.8766 | 0.041 | 0.010 | 0.625 | 0.575 | 1.839 | 0.000 | 7.299 | -2.194 | 2.677 | 5.854 |
| 149 | 260 | 222.8766 | 0.041 | 0.010 | 0.623 | 0.575 | 1.839 | 0.000 | 7.299 | -2.248 | 2.677 | 5.849 |
| 150 | 3 | 228.5562 | 0.042 | 0.020 | 0.807 | 1.127 | 3.607 | 0.000 | 7.341 | -2.165 | 2.431 | 6.960 |
| 151 | 59 | 228.5562 | 0.042 | 0.020 | 0.817 | 1.127 | 3.606 | 0.000 | 7.345 | -1.508 | 2.431 | 6.632 |
| 152 | 195 | 228.5562 | 0.042 | 0.020 | 0.814 | 1.127 | 3.606 | 0.000 | 7.344 | -1.578 | 2.431 | 6.631 |
| 153 | 12 | 254.7139 | 0.041 | 0.017 | 0.759 | 0.931 | 2.978 | 0.000 | 7.329 | -1.824 | 2.514 | 6.505 |
| 154 | 68 | 254.7139 | 0.042 | 0.017 | 0.762 | 0.930 | 2.977 | 0.000 | 7.331 | -1.456 | 2.514 | 6.226 |
| 155 | 204 | 254.7139 | 0.042 | 0.017 | 0.759 | 0.930 | 2.977 | 0.000 | 7.330 | -1.517 | 2.514 | 6.224 |
| 156 | 36 | 264.5698 | 0.039 | 0.011 | 0.606 | 0.591 | 1.892 | 0.000 | 7.280 | -2.009 | 2.691 | 5.564 |
| 157 | 92 | 264.5698 | 0.039 | 0.011 | 0.609 | 0.591 | 1.892 | 0.000 | 7.283 | -1.877 | 2.691 | 5.304 |
| 158 | 228 | 264.5698 | 0.039 | 0.011 | 0.607 | 0.591 | 1.892 | 0.000 | 7.282 | -1.923 | 2.691 | 5.300 |
| 159 | 32 | 333.6127 | 0.037 | 0.010 | 0.571 | 0.578 | 1.850 | 0.000 | 7.257 | -1.894 | 2.734 | 4.594 |
| 160 | 88 | 333.6127 | 0.037 | 0.010 | 0.575 | 0.578 | 1.850 | 0.000 | 7.259 | -1.868 | 2.734 | 4.366 |
| 161 | 224 | 333.6127 | 0.037 | 0.010 | 0.573 | 0.578 | 1.850 | 0.000 | 7.259 | -1.905 | 2.734 | 4.363 |
| 162 | 23 | 333.8201 | 0.038 | 0.012 | 0.637 | 0.690 | 2.207 | 0.000 | 7.277 | -1.401 | 2.669 | 5.255 |
| 163 | 79 | 333.8201 | 0.038 | 0.012 | 0.638 | 0.690 | 2.207 | 0.000 | 7.280 | -1.340 | 2.669 | 5.023 |
| 164 | 215 | 333.8201 | 0.038 | 0.012 | 0.636 | 0.690 | 2.207 | 0.000 | 7.279 | -1.381 | 2.669 | 5.021 |

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δ_t | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\delta_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil(ss)}$ | α_{ss} |
|-----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------|----------------------|---------------|---------------|
| 165 | 123 | 357.0172 | 0.036 | 0.010 | 0.558 | 0.559 | 1.788 | 0.000 | 7.253 | -2.196 | 2.756 | 4.038 |
| 166 | 257 | 357.0172 | 0.036 | 0.010 | 0.556 | 0.559 | 1.788 | 0.000 | 7.253 | -2.230 | 2.756 | 4.035 |
| 167 | 27 | 416.6143 | 0.035 | 0.010 | 0.543 | 0.566 | 1.811 | 0.000 | 7.243 | -1.915 | 2.773 | 3.904 |
| 168 | 83 | 416.6143 | 0.035 | 0.010 | 0.547 | 0.566 | 1.810 | 0.000 | 7.245 | -1.929 | 2.773 | 3.686 |
| 169 | 219 | 416.6143 | 0.035 | 0.010 | 0.545 | 0.566 | 1.810 | 0.000 | 7.244 | -1.958 | 2.773 | 3.684 |
| 170 | 13 | 499.2391 | 0.034 | 0.012 | 0.584 | 0.663 | 2.122 | 0.000 | 7.244 | -1.392 | 2.747 | 3.840 |
| 171 | 69 | 499.2391 | 0.034 | 0.012 | 0.585 | 0.663 | 2.122 | 0.000 | 7.246 | -1.381 | 2.747 | 3.631 |
| 172 | 205 | 499.2391 | 0.034 | 0.012 | 0.583 | 0.663 | 2.122 | 0.000 | 7.245 | -1.408 | 2.747 | 3.630 |
| 173 | 24 | 503.8640 | 0.033 | 0.010 | 0.520 | 0.561 | 1.794 | 0.000 | 7.228 | -1.829 | 2.801 | 3.385 |
| 174 | 80 | 503.8640 | 0.033 | 0.010 | 0.524 | 0.561 | 1.794 | 0.000 | 7.231 | -1.878 | 2.801 | 3.182 |
| 175 | 216 | 503.8640 | 0.033 | 0.010 | 0.522 | 0.561 | 1.794 | 0.000 | 7.230 | -1.903 | 2.801 | 3.180 |
| 176 | 4 | 514.2514 | 0.035 | 0.013 | 0.626 | 0.749 | 2.398 | 0.000 | 7.252 | -1.511 | 2.713 | 3.871 |
| 177 | 60 | 514.2514 | 0.035 | 0.013 | 0.625 | 0.749 | 2.397 | 0.000 | 7.253 | -1.436 | 2.713 | 3.672 |
| 178 | 196 | 514.2514 | 0.035 | 0.013 | 0.623 | 0.749 | 2.397 | 0.000 | 7.252 | -1.464 | 2.713 | 3.671 |
| 179 | 120 | 551.8250 | 0.032 | 0.010 | 0.499 | 0.536 | 1.714 | 0.000 | 7.218 | -2.263 | 2.826 | 2.821 |
| 180 | 254 | 551.8250 | 0.032 | 0.010 | 0.497 | 0.536 | 1.714 | 0.000 | 7.218 | -2.285 | 2.826 | 2.819 |
| 181 | 18 | 618.5337 | 0.030 | 0.010 | 0.494 | 0.550 | 1.760 | 0.000 | 7.208 | -1.845 | 2.833 | 2.873 |
| 182 | 74 | 618.5337 | 0.031 | 0.010 | 0.496 | 0.550 | 1.759 | 0.000 | 7.211 | -1.921 | 2.833 | 2.683 |
| 183 | 210 | 618.5337 | 0.031 | 0.010 | 0.494 | 0.550 | 1.759 | 0.000 | 7.210 | -1.941 | 2.833 | 2.681 |
| 184 | 5 | 699.9532 | 0.030 | 0.012 | 0.539 | 0.642 | 2.054 | 0.000 | 7.216 | -1.467 | 2.806 | 2.930 |
| 185 | 61 | 699.9532 | 0.031 | 0.012 | 0.539 | 0.642 | 2.054 | 0.000 | 7.218 | -1.523 | 2.806 | 2.750 |
| 186 | 197 | 699.9532 | 0.031 | 0.012 | 0.537 | 0.642 | 2.054 | 0.000 | 7.218 | -1.542 | 2.806 | 2.749 |
| 187 | 14 | 771.1717 | 0.028 | 0.010 | 0.452 | 0.533 | 1.707 | 0.000 | 7.179 | -2.320 | 2.865 | 2.431 |
| 188 | 70 | 771.1717 | 0.029 | 0.010 | 0.455 | 0.533 | 1.707 | 0.000 | 7.184 | -2.415 | 2.865 | 2.256 |
| 189 | 206 | 771.1717 | 0.029 | 0.010 | 0.454 | 0.533 | 1.707 | 0.000 | 7.183 | -2.431 | 2.865 | 2.254 |
| 190 | 117 | 825.2729 | 0.028 | 0.009 | 0.434 | 0.516 | 1.650 | 0.000 | 7.170 | -2.696 | 2.879 | 2.071 |
| 191 | 252 | 825.2729 | 0.028 | 0.009 | 0.432 | 0.516 | 1.650 | 0.000 | 7.169 | -2.711 | 2.879 | 2.069 |
| 192 | 9 | 954.4603 | 0.026 | 0.009 | 0.411 | 0.518 | 1.657 | 0.000 | 7.145 | -2.466 | 2.891 | 2.078 |
| 193 | 65 | 954.4603 | 0.027 | 0.009 | 0.417 | 0.518 | 1.657 | 0.000 | 7.151 | -2.576 | 2.891 | 1.910 |
| 194 | 201 | 954.4603 | 0.027 | 0.009 | 0.415 | 0.518 | 1.657 | 0.000 | 7.150 | -2.589 | 2.891 | 1.908 |
| 195 | 6 | 1106.2120 | 0.025 | 0.009 | 0.381 | 0.511 | 1.634 | 0.000 | 7.118 | -2.507 | 2.906 | 1.886 |
| 196 | 62 | 1106.2120 | 0.026 | 0.009 | 0.386 | 0.511 | 1.634 | 0.000 | 7.125 | -2.629 | 2.906 | 1.720 |
| 197 | 198 | 1106.2120 | 0.026 | 0.009 | 0.385 | 0.511 | 1.634 | 0.000 | 7.124 | -2.640 | 2.906 | 1.719 |
| 198 | 114 | 1157.0650 | 0.025 | 0.009 | 0.371 | 0.499 | 1.597 | 0.000 | 7.112 | -2.810 | 2.913 | 1.635 |
| 199 | 249 | 1157.0650 | 0.025 | 0.009 | 0.369 | 0.499 | 1.597 | 0.000 | 7.110 | -2.820 | 2.913 | 1.634 |

C.2 Longitudinal Unit C_{cmd} Step Input Time Response (25% Stabilator Failure)

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δt | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\dot{\delta}_{elev(mar)}$ | $\delta_{elev(max)}$ | $g_{pi(ss)}$ | α_{ss} |
|----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------------|----------------------|--------------|---------------|
| 1 | 119 | 65.4696 | 0.123 | 0.029 | 1.122 | 1.630 | 5.215 | 0.020 | 7.414 | 0.705 | 2.197 | 19.044 |
| 2 | 253 | 65.4696 | 0.186 | 0.029 | 1.232 | 1.630 | 5.215 | 0.017 | 7.425 | 0.673 | 2.197 | 19.050 |
| 3 | 118 | 65.5666 | 0.122 | 0.032 | 1.130 | 1.769 | 5.661 | 0.081 | 7.414 | 0.739 | 2.183 | 18.919 |
| 4 | 122 | 67.0399 | 0.184 | 0.024 | 1.213 | 1.347 | 4.311 | 0.015 | 7.424 | 0.805 | 2.237 | 18.920 |
| 5 | 256 | 67.0399 | 0.183 | 0.024 | 1.213 | 1.347 | 4.312 | 0.014 | 7.424 | 0.540 | 2.237 | 18.925 |
| 6 | 121 | 67.4267 | 0.184 | 0.026 | 1.220 | 1.469 | 4.702 | 0.013 | 7.425 | 0.843 | 2.219 | 18.712 |
| 7 | 255 | 67.4267 | 0.183 | 0.026 | 1.220 | 1.469 | 4.702 | 0.017 | 7.424 | 0.578 | 2.219 | 18.717 |
| 8 | 124 | 67.6717 | 0.182 | 0.022 | 1.205 | 1.220 | 3.904 | 0.013 | 7.424 | 0.737 | 2.259 | 18.921 |
| 9 | 116 | 68.8746 | 0.182 | 0.034 | 1.245 | 1.862 | 5.959 | 0.016 | 7.425 | 0.874 | 2.177 | 18.066 |
| 10 | 251 | 68.8746 | 0.181 | 0.034 | 1.245 | 1.862 | 5.959 | 0.018 | 7.425 | 0.611 | 2.177 | 18.073 |
| 11 | 115 | 70.9929 | 0.179 | 0.036 | 1.251 | 1.976 | 6.325 | 0.016 | 7.424 | 0.821 | 2.169 | 17.521 |
| 12 | 10 | 74.2746 | 0.168 | 0.032 | 1.228 | 1.789 | 5.725 | 0.015 | 7.423 | -1.030 | 2.189 | 17.643 |
| 13 | 66 | 74.2746 | 0.176 | 0.032 | 1.233 | 1.783 | 5.707 | 0.012 | 7.424 | 0.633 | 2.189 | 16.988 |
| 14 | 202 | 74.2746 | 0.175 | 0.032 | 1.233 | 1.784 | 5.707 | 0.016 | 7.424 | 0.388 | 2.189 | 16.993 |
| 15 | 113 | 75.5664 | 0.174 | 0.036 | 1.251 | 2.025 | 6.479 | 0.016 | 7.424 | 0.661 | 2.169 | 16.564 |
| 16 | 250 | 77.0323 | 0.171 | 0.034 | 1.240 | 1.887 | 6.038 | 0.017 | 7.423 | 0.335 | 2.182 | 16.394 |
| 17 | 258 | 77.2143 | 0.178 | 0.020 | 1.150 | 1.130 | 3.617 | 0.000 | 7.422 | 0.432 | 2.291 | 17.020 |
| 18 | 125 | 77.2914 | 0.175 | 0.018 | 1.150 | 1.007 | 3.223 | 0.000 | 7.421 | 0.666 | 2.320 | 17.195 |
| 19 | 259 | 77.2914 | 0.174 | 0.018 | 1.151 | 1.007 | 3.223 | 0.000 | 7.421 | 0.440 | 2.320 | 17.194 |
| 20 | 37 | 80.2356 | 0.167 | 0.018 | 1.149 | 0.988 | 3.163 | 0.000 | 7.420 | -0.089 | 2.328 | 17.187 |
| 21 | 93 | 80.2356 | 0.169 | 0.018 | 1.142 | 0.986 | 3.154 | 0.000 | 7.420 | 0.668 | 2.330 | 16.575 |
| 22 | 229 | 80.2356 | 0.167 | 0.018 | 1.144 | 0.986 | 3.154 | 0.000 | 7.420 | 0.452 | 2.330 | 16.573 |
| 23 | 15 | 80.3692 | 0.176 | 0.028 | 1.152 | 1.578 | 5.050 | 0.002 | 7.421 | -0.775 | 2.219 | 16.494 |
| 24 | 71 | 80.3692 | 0.184 | 0.028 | 1.144 | 1.574 | 5.035 | 0.004 | 7.422 | 0.647 | 2.219 | 15.838 |
| 25 | 207 | 80.3692 | 0.182 | 0.028 | 1.146 | 1.574 | 5.035 | 0.004 | 7.422 | 0.423 | 2.219 | 15.842 |
| 26 | 33 | 80.5349 | 0.169 | 0.020 | 1.149 | 1.106 | 3.540 | 0.000 | 7.420 | -0.319 | 2.299 | 16.977 |
| 27 | 89 | 80.5349 | 0.173 | 0.020 | 1.140 | 1.103 | 3.531 | 0.000 | 7.421 | 0.613 | 2.301 | 16.348 |
| 28 | 225 | 80.5349 | 0.171 | 0.020 | 1.143 | 1.103 | 3.531 | 0.000 | 7.421 | 0.396 | 2.301 | 16.348 |
| 29 | 28 | 81.4969 | 0.169 | 0.022 | 1.147 | 1.207 | 3.863 | 0.000 | 7.420 | -0.487 | 2.279 | 16.662 |
| 30 | 84 | 81.4969 | 0.174 | 0.022 | 1.139 | 1.204 | 3.853 | 0.000 | 7.421 | 0.575 | 2.281 | 16.030 |
| 31 | 220 | 81.4969 | 0.172 | 0.022 | 1.141 | 1.204 | 3.853 | 0.000 | 7.421 | 0.359 | 2.281 | 16.031 |
| 32 | 1 | 82.2802 | 0.178 | 0.035 | 1.145 | 1.936 | 6.194 | 0.008 | 7.421 | -1.366 | 2.182 | 16.023 |
| 33 | 57 | 82.2802 | 0.189 | 0.035 | 1.131 | 1.931 | 6.178 | 0.008 | 7.422 | 0.121 | 2.182 | 15.412 |
| 34 | 193 | 82.2802 | 0.187 | 0.035 | 1.134 | 1.931 | 6.178 | 0.009 | 7.422 | -0.100 | 2.182 | 15.416 |
| 35 | 7 | 83.3181 | 0.177 | 0.033 | 1.138 | 1.811 | 5.795 | 0.006 | 7.421 | -1.393 | 2.194 | 15.951 |
| 36 | 63 | 83.3181 | 0.187 | 0.033 | 1.124 | 1.806 | 5.780 | 0.006 | 7.421 | 0.020 | 2.195 | 15.351 |
| 37 | 199 | 83.3181 | 0.185 | 0.033 | 1.127 | 1.806 | 5.780 | 0.007 | 7.421 | -0.197 | 2.195 | 15.355 |
| 38 | 19 | 83.4550 | 0.169 | 0.026 | 1.146 | 1.421 | 4.549 | 0.000 | 7.420 | -0.755 | 2.244 | 16.067 |
| 39 | 75 | 83.4550 | 0.175 | 0.026 | 1.139 | 1.418 | 4.537 | 0.000 | 7.421 | 0.523 | 2.244 | 15.429 |
| 40 | 211 | 83.4550 | 0.173 | 0.026 | 1.142 | 1.418 | 4.537 | 0.000 | 7.421 | 0.311 | 2.244 | 15.432 |

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δt | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil(ss)}$ | α_{ss} |
|----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------------|----------------------|---------------|---------------|
| 42 | 81 | 83.7191 | 0.173 | 0.023 | 1.135 | 1.298 | 4.153 | 0.000 | 7.420 | 0.528 | 2.265 | 15.507 |
| 43 | 217 | 83.7191 | 0.171 | 0.023 | 1.138 | 1.298 | 4.153 | 0.000 | 7.420 | 0.318 | 2.265 | 15.509 |
| 44 | 34 | 87.3860 | 0.157 | 0.019 | 1.133 | 1.056 | 3.379 | 0.000 | 7.418 | -0.211 | 2.320 | 15.682 |
| 45 | 90 | 87.3860 | 0.160 | 0.019 | 1.125 | 1.054 | 3.371 | 0.000 | 7.418 | 0.590 | 2.322 | 15.095 |
| 46 | 226 | 87.3860 | 0.158 | 0.019 | 1.127 | 1.054 | 3.371 | 0.000 | 7.418 | 0.395 | 2.322 | 15.094 |
| 47 | 127 | 88.7159 | 0.168 | 0.015 | 1.029 | 0.825 | 2.641 | 0.000 | 7.416 | 0.618 | 2.406 | 14.778 |
| 48 | 261 | 88.7159 | 0.166 | 0.015 | 1.032 | 0.825 | 2.641 | 0.000 | 7.416 | 0.435 | 2.406 | 14.775 |
| 49 | 38 | 89.3983 | 0.150 | 0.017 | 1.127 | 0.929 | 2.973 | 0.000 | 7.417 | 0.142 | 2.358 | 15.413 |
| 50 | 94 | 89.3983 | 0.178 | 0.017 | 1.024 | 0.927 | 2.967 | 0.000 | 7.417 | 0.644 | 2.368 | 14.692 |
| 51 | 230 | 89.3983 | 0.176 | 0.017 | 1.027 | 0.927 | 2.967 | 0.000 | 7.417 | 0.455 | 2.368 | 14.690 |
| 52 | 11 | 91.6970 | 0.163 | 0.029 | 1.118 | 1.590 | 5.088 | 0.002 | 7.418 | -1.790 | 2.227 | 14.904 |
| 53 | 67 | 91.6970 | 0.171 | 0.029 | 1.110 | 1.586 | 5.076 | 0.005 | 7.419 | -0.449 | 2.228 | 14.298 |
| 54 | 203 | 91.6970 | 0.168 | 0.029 | 1.114 | 1.586 | 5.076 | 0.003 | 7.419 | -0.642 | 2.228 | 14.300 |
| 55 | 41 | 94.3473 | 0.155 | 0.014 | 1.023 | 0.799 | 2.557 | 0.000 | 7.413 | -0.015 | 2.424 | 14.393 |
| 56 | 97 | 94.3473 | 0.155 | 0.014 | 1.019 | 0.798 | 2.553 | 0.000 | 7.413 | 0.401 | 2.425 | 13.904 |
| 57 | 233 | 94.3473 | 0.154 | 0.014 | 1.021 | 0.798 | 2.553 | 0.000 | 7.413 | 0.233 | 2.425 | 13.900 |
| 58 | 262 | 101.0962 | 0.123 | 0.012 | 1.021 | 0.681 | 2.179 | 0.000 | 7.407 | 0.103 | 2.489 | 12.825 |
| 59 | 16 | 102.4478 | 0.155 | 0.025 | 1.068 | 1.379 | 4.412 | 0.000 | 7.414 | -1.030 | 2.269 | 13.231 |
| 60 | 72 | 102.4478 | 0.163 | 0.025 | 1.054 | 1.376 | 4.404 | 0.003 | 7.415 | 0.006 | 2.270 | 12.676 |
| 61 | 208 | 102.4478 | 0.160 | 0.025 | 1.058 | 1.376 | 4.404 | 0.003 | 7.415 | -0.163 | 2.270 | 12.675 |
| 62 | 263 | 103.7392 | 0.130 | 0.012 | 0.982 | 0.672 | 2.149 | 0.000 | 7.406 | 0.029 | 2.502 | 12.856 |
| 63 | 42 | 106.1299 | 0.133 | 0.013 | 1.001 | 0.750 | 2.399 | 0.000 | 7.408 | -0.377 | 2.462 | 12.825 |
| 64 | 98 | 106.1299 | 0.136 | 0.013 | 0.998 | 0.749 | 2.395 | 0.000 | 7.408 | 0.080 | 2.462 | 12.683 |
| 65 | 234 | 106.1299 | 0.134 | 0.013 | 1.000 | 0.749 | 2.395 | 0.000 | 7.408 | -0.064 | 2.462 | 12.675 |
| 66 | 264 | 106.4162 | 0.125 | 0.012 | 0.976 | 0.662 | 2.119 | 0.000 | 7.404 | -0.050 | 2.511 | 12.472 |
| 67 | 20 | 109.0025 | 0.149 | 0.022 | 1.042 | 1.227 | 3.925 | 0.000 | 7.412 | -1.009 | 2.306 | 12.503 |
| 68 | 76 | 109.0025 | 0.155 | 0.022 | 1.030 | 1.225 | 3.920 | 0.001 | 7.413 | -0.174 | 2.306 | 11.997 |
| 69 | 212 | 109.0025 | 0.153 | 0.022 | 1.033 | 1.225 | 3.920 | 0.000 | 7.413 | -0.329 | 2.306 | 11.996 |
| 70 | 46 | 109.1273 | 0.115 | 0.012 | 0.994 | 0.654 | 2.094 | 0.000 | 7.403 | -0.537 | 2.515 | 12.710 |
| 71 | 102 | 109.1273 | 0.121 | 0.012 | 0.970 | 0.653 | 2.091 | 0.000 | 7.403 | 0.006 | 2.520 | 12.110 |
| 72 | 238 | 109.1273 | 0.120 | 0.012 | 0.971 | 0.653 | 2.091 | 0.000 | 7.403 | -0.124 | 2.520 | 12.098 |
| 73 | 29 | 110.1905 | 0.149 | 0.018 | 1.012 | 1.022 | 3.269 | 0.000 | 7.411 | -0.682 | 2.360 | 12.408 |
| 74 | 85 | 110.1905 | 0.153 | 0.018 | 1.002 | 1.020 | 3.265 | 0.000 | 7.411 | -0.153 | 2.361 | 11.957 |
| 75 | 221 | 110.1905 | 0.151 | 0.018 | 1.005 | 1.020 | 3.265 | 0.000 | 7.411 | -0.304 | 2.361 | 11.955 |
| 76 | 8 | 110.9265 | 0.144 | 0.028 | 1.079 | 1.547 | 4.951 | 0.001 | 7.412 | -1.992 | 2.250 | 12.446 |
| 77 | 64 | 110.9265 | 0.153 | 0.028 | 1.065 | 1.544 | 4.942 | 0.005 | 7.413 | -0.759 | 2.250 | 11.856 |
| 78 | 200 | 110.9265 | 0.150 | 0.028 | 1.069 | 1.544 | 4.942 | 0.005 | 7.413 | -0.914 | 2.250 | 11.856 |
| 79 | 47 | 111.8726 | 0.108 | 0.012 | 0.998 | 0.646 | 2.066 | 0.000 | 7.401 | -0.811 | 2.522 | 12.291 |
| 80 | 103 | 111.8726 | 0.113 | 0.012 | 0.975 | 0.645 | 2.063 | 0.000 | 7.401 | -0.281 | 2.527 | 11.705 |
| 81 | 239 | 111.8726 | 0.112 | 0.012 | 0.976 | 0.645 | 2.063 | 0.000 | 7.401 | -0.405 | 2.527 | 11.693 |
| 82 | 48 | 114.6519 | 0.101 | 0.011 | 1.000 | 0.637 | 2.039 | 0.000 | 7.400 | -1.048 | 2.529 | 11.882 |

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δt | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil(ss)}$ | α_{ss} |
|-----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------------|----------------------|---------------|---------------|
| 83 | 104 | 114.6519 | 0.106 | 0.011 | 0.978 | 0.636 | 2.036 | 0.000 | 7.400 | -0.531 | 2.535 | 11.308 |
| 84 | 240 | 114.6519 | 0.104 | 0.011 | 0.980 | 0.636 | 2.036 | 0.000 | 7.399 | -0.651 | 2.534 | 11.296 |
| 85 | 49 | 117.4653 | 0.095 | 0.011 | 1.001 | 0.629 | 2.012 | 0.000 | 7.398 | -1.252 | 2.535 | 11.483 |
| 86 | 105 | 117.4653 | 0.099 | 0.011 | 0.980 | 0.628 | 2.009 | 0.000 | 7.398 | -0.750 | 2.542 | 10.919 |
| 87 | 241 | 117.4653 | 0.097 | 0.011 | 0.982 | 0.628 | 2.009 | 0.000 | 7.397 | -0.864 | 2.541 | 10.906 |
| 88 | 50 | 120.3129 | 0.089 | 0.011 | 1.000 | 0.621 | 1.986 | 0.000 | 7.396 | -1.427 | 2.542 | 11.091 |
| 89 | 106 | 120.3129 | 0.092 | 0.011 | 0.980 | 0.620 | 1.984 | 0.000 | 7.396 | -0.940 | 2.549 | 10.536 |
| 90 | 242 | 120.3129 | 0.091 | 0.011 | 0.982 | 0.620 | 1.984 | 0.000 | 7.395 | -1.050 | 2.548 | 10.523 |
| 91 | 43 | 121.8328 | 0.108 | 0.013 | 0.982 | 0.696 | 2.227 | 0.000 | 7.400 | -0.689 | 2.507 | 11.321 |
| 92 | 99 | 121.8328 | 0.113 | 0.013 | 0.962 | 0.695 | 2.224 | 0.000 | 7.400 | -0.284 | 2.510 | 10.787 |
| 93 | 235 | 121.8328 | 0.112 | 0.013 | 0.964 | 0.695 | 2.224 | 0.000 | 7.400 | -0.402 | 2.510 | 10.780 |
| 94 | 51 | 123.1945 | 0.083 | 0.011 | 0.999 | 0.613 | 1.961 | 0.000 | 7.394 | -1.575 | 2.549 | 10.708 |
| 95 | 107 | 123.1945 | 0.103 | 0.011 | 0.903 | 0.612 | 1.959 | 0.000 | 7.394 | -1.138 | 2.567 | 9.668 |
| 96 | 243 | 123.1945 | 0.101 | 0.011 | 0.906 | 0.612 | 1.959 | 0.000 | 7.394 | -1.244 | 2.567 | 9.661 |
| 97 | 52 | 126.1103 | 0.094 | 0.011 | 0.922 | 0.605 | 1.937 | 0.000 | 7.392 | -1.713 | 2.575 | 9.866 |
| 98 | 108 | 126.1103 | 0.099 | 0.011 | 0.896 | 0.605 | 1.935 | 0.000 | 7.392 | -1.330 | 2.576 | 9.427 |
| 99 | 244 | 126.1103 | 0.098 | 0.011 | 0.898 | 0.605 | 1.935 | 0.000 | 7.392 | -1.432 | 2.576 | 9.420 |
| 100 | 53 | 129.0601 | 0.091 | 0.011 | 0.915 | 0.598 | 1.914 | 0.000 | 7.390 | -1.882 | 2.583 | 9.625 |
| 101 | 109 | 129.0601 | 0.096 | 0.011 | 0.889 | 0.598 | 1.912 | 0.000 | 7.390 | -1.525 | 2.584 | 9.179 |
| 102 | 245 | 129.0601 | 0.095 | 0.011 | 0.891 | 0.598 | 1.912 | 0.000 | 7.390 | -1.624 | 2.584 | 9.172 |
| 103 | 2 | 129.4213 | 0.125 | 0.027 | 1.079 | 1.512 | 4.840 | 0.000 | 7.408 | -2.037 | 2.270 | 10.750 |
| 104 | 58 | 129.4213 | 0.134 | 0.027 | 1.068 | 1.510 | 4.832 | 0.003 | 7.409 | -0.870 | 2.270 | 10.190 |
| 105 | 194 | 129.4213 | 0.132 | 0.027 | 1.071 | 1.510 | 4.832 | 0.003 | 7.409 | -1.003 | 2.270 | 10.189 |
| 106 | 17 | 129.8252 | 0.126 | 0.022 | 1.045 | 1.214 | 3.886 | 0.000 | 7.407 | -1.290 | 2.328 | 10.668 |
| 107 | 73 | 129.8252 | 0.132 | 0.022 | 1.037 | 1.213 | 3.881 | 0.000 | 7.408 | -0.485 | 2.328 | 10.168 |
| 108 | 209 | 129.8252 | 0.131 | 0.022 | 1.039 | 1.213 | 3.881 | 0.000 | 7.408 | -0.615 | 2.328 | 10.167 |
| 109 | 30 | 129.9582 | 0.124 | 0.017 | 1.017 | 0.936 | 2.994 | 0.000 | 7.405 | -0.754 | 2.409 | 10.710 |
| 110 | 86 | 129.9582 | 0.127 | 0.017 | 1.009 | 0.935 | 2.991 | 0.000 | 7.406 | -0.373 | 2.409 | 10.269 |
| 111 | 222 | 129.9582 | 0.125 | 0.017 | 1.012 | 0.935 | 2.991 | 0.000 | 7.406 | -0.498 | 2.409 | 10.266 |
| 112 | 26 | 130.0074 | 0.125 | 0.018 | 1.026 | 1.024 | 3.276 | 0.000 | 7.406 | -0.970 | 2.379 | 10.699 |
| 113 | 82 | 130.0074 | 0.129 | 0.018 | 1.018 | 1.023 | 3.273 | 0.000 | 7.407 | -0.430 | 2.380 | 10.236 |
| 114 | 218 | 130.0074 | 0.127 | 0.018 | 1.021 | 1.023 | 3.273 | 0.000 | 7.407 | -0.557 | 2.380 | 10.234 |
| 115 | 35 | 130.0653 | 0.121 | 0.015 | 1.006 | 0.851 | 2.723 | 0.000 | 7.404 | -0.547 | 2.442 | 10.685 |
| 116 | 91 | 130.0653 | 0.124 | 0.015 | 0.997 | 0.850 | 2.721 | 0.000 | 7.405 | -0.306 | 2.442 | 10.268 |
| 117 | 227 | 130.0653 | 0.122 | 0.015 | 1.000 | 0.850 | 2.721 | 0.000 | 7.404 | -0.429 | 2.442 | 10.265 |
| 118 | 21 | 130.1006 | 0.125 | 0.020 | 1.036 | 1.116 | 3.572 | 0.000 | 7.406 | -1.148 | 2.353 | 10.670 |
| 119 | 77 | 130.1006 | 0.131 | 0.020 | 1.027 | 1.115 | 3.567 | 0.000 | 7.407 | -0.467 | 2.353 | 10.187 |
| 120 | 213 | 130.1006 | 0.129 | 0.020 | 1.030 | 1.115 | 3.567 | 0.000 | 7.407 | -0.595 | 2.353 | 10.185 |
| 121 | 44 | 131.7744 | 0.100 | 0.012 | 0.934 | 0.668 | 2.136 | 0.000 | 7.395 | -0.823 | 2.539 | 9.571 |
| 122 | 100 | 131.7744 | 0.108 | 0.012 | 0.907 | 0.667 | 2.135 | 0.000 | 7.395 | -0.470 | 2.539 | 9.186 |
| 123 | 236 | 131.7744 | 0.106 | 0.012 | 0.910 | 0.667 | 2.135 | 0.000 | 7.395 | -0.576 | 2.539 | 9.182 |

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δt | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil(ss)}$ | α_{ss} |
|-----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------------|----------------------|---------------|---------------|
| 124 | 54 | 132.0441 | 0.088 | 0.011 | 0.908 | 0.591 | 1.891 | 0.000 | 7.388 | -2.053 | 2.592 | 9.375 |
| 125 | 110 | 132.0441 | 0.093 | 0.011 | 0.882 | 0.590 | 1.889 | 0.000 | 7.388 | -1.722 | 2.593 | 8.923 |
| 126 | 246 | 132.0441 | 0.091 | 0.011 | 0.885 | 0.590 | 1.889 | 0.000 | 7.388 | -1.818 | 2.593 | 8.916 |
| 127 | 39 | 134.8266 | 0.105 | 0.013 | 0.976 | 0.744 | 2.381 | 0.000 | 7.398 | -0.763 | 2.496 | 10.173 |
| 128 | 95 | 134.8266 | 0.118 | 0.013 | 0.920 | 0.744 | 2.379 | 0.000 | 7.398 | -0.479 | 2.498 | 9.145 |
| 129 | 231 | 134.8266 | 0.116 | 0.013 | 0.923 | 0.743 | 2.379 | 0.000 | 7.398 | -0.589 | 2.498 | 9.143 |
| 130 | 55 | 135.0621 | 0.085 | 0.011 | 0.901 | 0.584 | 1.869 | 0.000 | 7.387 | -2.228 | 2.600 | 9.117 |
| 131 | 111 | 135.0621 | 0.090 | 0.011 | 0.876 | 0.584 | 1.867 | 0.000 | 7.386 | -1.922 | 2.601 | 8.660 |
| 132 | 247 | 135.0621 | 0.089 | 0.011 | 0.877 | 0.584 | 1.867 | 0.000 | 7.386 | -2.015 | 2.601 | 8.653 |
| 133 | 56 | 138.1142 | 0.082 | 0.010 | 0.894 | 0.577 | 1.847 | 0.000 | 7.385 | -2.407 | 2.608 | 8.853 |
| 134 | 112 | 138.1142 | 0.087 | 0.010 | 0.869 | 0.577 | 1.846 | 0.000 | 7.384 | -2.125 | 2.609 | 8.389 |
| 135 | 248 | 138.1142 | 0.086 | 0.010 | 0.871 | 0.577 | 1.846 | 0.000 | 7.384 | -2.215 | 2.609 | 8.382 |
| 136 | 45 | 167.7286 | 0.069 | 0.011 | 0.866 | 0.589 | 1.885 | 0.000 | 7.374 | -2.413 | 2.626 | 7.292 |
| 137 | 101 | 167.7286 | 0.053 | 0.011 | 0.942 | 0.589 | 1.884 | 0.000 | 7.374 | -2.171 | 2.625 | 6.539 |
| 138 | 237 | 167.7286 | 0.052 | 0.011 | 0.944 | 0.589 | 1.884 | 0.000 | 7.374 | -2.244 | 2.625 | 6.535 |
| 139 | 22 | 170.3164 | 0.112 | 0.017 | 0.942 | 0.970 | 3.105 | 0.006 | 7.395 | -1.330 | 2.434 | 7.916 |
| 140 | 78 | 170.3164 | 0.116 | 0.017 | 0.930 | 0.970 | 3.103 | 0.007 | 7.396 | -0.950 | 2.434 | 7.600 |
| 141 | 214 | 170.3164 | 0.114 | 0.017 | 0.934 | 0.970 | 3.103 | 0.007 | 7.396 | -1.045 | 2.434 | 7.600 |
| 142 | 40 | 208.2658 | 0.044 | 0.011 | 0.886 | 0.595 | 1.904 | 0.000 | 7.359 | -2.168 | 2.652 | 5.737 |
| 143 | 96 | 208.2658 | 0.045 | 0.011 | 0.887 | 0.595 | 1.904 | 0.000 | 7.360 | -1.957 | 2.653 | 5.463 |
| 144 | 232 | 208.2658 | 0.045 | 0.011 | 0.884 | 0.595 | 1.904 | 0.000 | 7.360 | -2.015 | 2.653 | 5.460 |
| 145 | 31 | 215.9733 | 0.056 | 0.013 | 0.944 | 0.720 | 2.305 | 0.000 | 7.372 | -1.413 | 2.581 | 6.348 |
| 146 | 87 | 215.9733 | 0.060 | 0.013 | 0.929 | 0.720 | 2.304 | 0.000 | 7.373 | -1.244 | 2.581 | 6.085 |
| 147 | 223 | 215.9733 | 0.058 | 0.013 | 0.933 | 0.720 | 2.304 | 0.000 | 7.372 | -1.309 | 2.581 | 6.084 |
| 148 | 126 | 222.8766 | 0.044 | 0.010 | 0.842 | 0.575 | 1.839 | 0.000 | 7.352 | -2.174 | 2.677 | 4.901 |
| 149 | 260 | 222.8766 | 0.044 | 0.010 | 0.839 | 0.575 | 1.839 | 0.000 | 7.351 | -2.227 | 2.677 | 4.899 |
| 150 | 3 | 228.5562 | 0.069 | 0.020 | 1.038 | 1.127 | 3.607 | 0.006 | 7.383 | -2.048 | 2.431 | 6.107 |
| 151 | 59 | 228.5562 | 0.073 | 0.020 | 1.029 | 1.127 | 3.606 | 0.005 | 7.385 | -1.389 | 2.431 | 5.794 |
| 152 | 195 | 228.5562 | 0.072 | 0.020 | 1.032 | 1.127 | 3.606 | 0.006 | 7.385 | -1.460 | 2.431 | 5.794 |
| 153 | 12 | 254.7139 | 0.060 | 0.017 | 0.982 | 0.931 | 2.978 | 0.000 | 7.374 | -1.753 | 2.514 | 5.609 |
| 154 | 68 | 254.7139 | 0.063 | 0.017 | 0.973 | 0.930 | 2.977 | 0.002 | 7.375 | -1.385 | 2.514 | 5.346 |
| 155 | 204 | 254.7139 | 0.062 | 0.017 | 0.976 | 0.930 | 2.977 | 0.001 | 7.375 | -1.446 | 2.514 | 5.346 |
| 156 | 36 | 264.5698 | 0.043 | 0.011 | 0.786 | 0.591 | 1.892 | 0.000 | 7.338 | -1.989 | 2.691 | 4.658 |
| 157 | 92 | 264.5698 | 0.043 | 0.011 | 0.790 | 0.591 | 1.892 | 0.000 | 7.340 | -1.858 | 2.691 | 4.416 |
| 158 | 228 | 264.5698 | 0.043 | 0.011 | 0.787 | 0.591 | 1.892 | 0.000 | 7.339 | -1.904 | 2.691 | 4.414 |
| 159 | 32 | 333.6127 | 0.041 | 0.010 | 0.696 | 0.578 | 1.850 | 0.000 | 7.312 | -1.876 | 2.734 | 3.826 |
| 160 | 88 | 333.6127 | 0.041 | 0.010 | 0.700 | 0.578 | 1.850 | 0.000 | 7.314 | -1.851 | 2.734 | 3.614 |
| 161 | 224 | 333.6127 | 0.041 | 0.010 | 0.698 | 0.578 | 1.850 | 0.000 | 7.314 | -1.888 | 2.734 | 3.612 |
| 162 | 23 | 333.8201 | 0.042 | 0.012 | 0.804 | 0.690 | 2.207 | 0.000 | 7.335 | -1.382 | 2.669 | 4.395 |
| 163 | 79 | 333.8201 | 0.042 | 0.012 | 0.805 | 0.690 | 2.207 | 0.002 | 7.337 | -1.322 | 2.669 | 4.180 |
| 164 | 215 | 333.8201 | 0.042 | 0.012 | 0.802 | 0.690 | 2.207 | 0.002 | 7.336 | -1.363 | 2.669 | 4.179 |

| # | srf# | \bar{q} | t_1 | Δt_{minL1} | Δt | Δt_{maxL1} | Δt_{maxL2} | $\frac{\Delta q_2}{\Delta q_1}$ | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil(ss)}$ | α_{ss} |
|-----|------|-----------|-------|--------------------|------------|--------------------|--------------------|---------------------------------|----------------------------|----------------------|---------------|---------------|
| 165 | 123 | 357.0172 | 0.040 | 0.010 | 0.662 | 0.559 | 1.788 | 0.000 | 7.301 | -2.179 | 2.756 | 3.328 |
| 166 | 257 | 357.0172 | 0.040 | 0.010 | 0.659 | 0.559 | 1.788 | 0.000 | 7.301 | -2.213 | 2.756 | 3.326 |
| 167 | 27 | 416.6143 | 0.039 | 0.010 | 0.618 | 0.566 | 1.811 | 0.000 | 7.280 | -1.899 | 2.773 | 3.225 |
| 168 | 83 | 416.6143 | 0.039 | 0.010 | 0.621 | 0.566 | 1.810 | 0.000 | 7.283 | -1.913 | 2.773 | 3.021 |
| 169 | 219 | 416.6143 | 0.039 | 0.010 | 0.619 | 0.566 | 1.810 | 0.000 | 7.282 | -1.943 | 2.773 | 3.020 |
| 170 | 13 | 499.2391 | 0.039 | 0.012 | 0.653 | 0.663 | 2.122 | 0.000 | 7.285 | -1.376 | 2.747 | 3.157 |
| 171 | 69 | 499.2391 | 0.039 | 0.012 | 0.654 | 0.663 | 2.122 | 0.000 | 7.287 | -1.365 | 2.747 | 2.961 |
| 172 | 205 | 499.2391 | 0.039 | 0.012 | 0.652 | 0.663 | 2.122 | 0.000 | 7.286 | -1.393 | 2.747 | 2.961 |
| 173 | 24 | 503.8640 | 0.038 | 0.010 | 0.557 | 0.561 | 1.794 | 0.000 | 7.259 | -1.817 | 2.801 | 2.785 |
| 174 | 80 | 503.8640 | 0.038 | 0.010 | 0.561 | 0.561 | 1.794 | 0.000 | 7.260 | -1.866 | 2.801 | 2.595 |
| 175 | 216 | 503.8640 | 0.038 | 0.010 | 0.559 | 0.561 | 1.794 | 0.000 | 7.260 | -1.890 | 2.801 | 2.594 |
| 176 | 4 | 514.2514 | 0.039 | 0.013 | 0.716 | 0.749 | 2.398 | 0.000 | 7.301 | -1.495 | 2.713 | 3.200 |
| 177 | 60 | 514.2514 | 0.039 | 0.013 | 0.716 | 0.749 | 2.397 | 0.000 | 7.303 | -1.420 | 2.713 | 3.013 |
| 178 | 196 | 514.2514 | 0.039 | 0.013 | 0.713 | 0.749 | 2.397 | 0.000 | 7.302 | -1.449 | 2.713 | 3.013 |
| 179 | 120 | 551.8250 | 0.037 | 0.010 | 0.514 | 0.536 | 1.714 | 0.000 | 7.251 | -2.251 | 2.826 | 2.308 |
| 180 | 254 | 551.8250 | 0.037 | 0.010 | 0.512 | 0.536 | 1.714 | 0.000 | 7.251 | -2.273 | 2.826 | 2.307 |
| 181 | 18 | 618.5337 | 0.036 | 0.010 | 0.493 | 0.550 | 1.760 | 0.000 | 7.244 | -1.833 | 2.833 | 2.358 |
| 182 | 74 | 618.5337 | 0.036 | 0.010 | 0.496 | 0.550 | 1.759 | 0.000 | 7.246 | -1.910 | 2.833 | 2.179 |
| 183 | 210 | 618.5337 | 0.036 | 0.010 | 0.494 | 0.550 | 1.759 | 0.000 | 7.246 | -1.930 | 2.833 | 2.178 |
| 184 | 5 | 699.9532 | 0.036 | 0.012 | 0.540 | 0.642 | 2.054 | 0.000 | 7.250 | -1.456 | 2.806 | 2.388 |
| 185 | 61 | 699.9532 | 0.037 | 0.012 | 0.539 | 0.642 | 2.054 | 0.000 | 7.252 | -1.512 | 2.806 | 2.219 |
| 186 | 197 | 699.9532 | 0.036 | 0.012 | 0.538 | 0.642 | 2.054 | 0.000 | 7.251 | -1.531 | 2.806 | 2.219 |
| 187 | 14 | 771.1717 | 0.035 | 0.010 | 0.421 | 0.533 | 1.707 | 0.000 | 7.223 | -2.309 | 2.865 | 2.010 |
| 188 | 70 | 771.1717 | 0.035 | 0.010 | 0.425 | 0.533 | 1.707 | 0.000 | 7.226 | -2.405 | 2.865 | 1.844 |
| 189 | 206 | 771.1717 | 0.035 | 0.010 | 0.423 | 0.533 | 1.707 | 0.000 | 7.225 | -2.421 | 2.865 | 1.843 |
| 190 | 117 | 825.2729 | 0.034 | 0.009 | 0.395 | 0.516 | 1.650 | 0.000 | 7.215 | -2.686 | 2.879 | 1.701 |
| 191 | 252 | 825.2729 | 0.034 | 0.009 | 0.393 | 0.516 | 1.650 | 0.000 | 7.215 | -2.701 | 2.879 | 1.700 |
| 192 | 9 | 954.4603 | 0.033 | 0.009 | 0.362 | 0.518 | 1.657 | 0.000 | 7.198 | -2.457 | 2.891 | 1.725 |
| 193 | 65 | 954.4603 | 0.034 | 0.009 | 0.364 | 0.518 | 1.657 | 0.000 | 7.201 | -2.567 | 2.891 | 1.564 |
| 194 | 201 | 954.4603 | 0.034 | 0.009 | 0.363 | 0.518 | 1.657 | 0.000 | 7.201 | -2.580 | 2.891 | 1.563 |
| 195 | 6 | 1106.2120 | 0.032 | 0.009 | 0.328 | 0.511 | 1.634 | 0.000 | 7.178 | -2.498 | 2.906 | 1.569 |
| 196 | 62 | 1106.2120 | 0.033 | 0.009 | 0.329 | 0.511 | 1.634 | 0.000 | 7.182 | -2.621 | 2.906 | 1.410 |
| 197 | 198 | 1106.2120 | 0.033 | 0.009 | 0.328 | 0.511 | 1.634 | 0.000 | 7.181 | -2.632 | 2.906 | 1.409 |
| 198 | 114 | 1157.0650 | 0.032 | 0.009 | 0.313 | 0.499 | 1.597 | 0.000 | 7.172 | -2.802 | 2.913 | 1.347 |
| 199 | 249 | 1157.0650 | 0.032 | 0.009 | 0.312 | 0.499 | 1.597 | 0.000 | 7.171 | -2.812 | 2.913 | 1.346 |

C.3 Longitudinal Maximum C_{cmd} Step Input Time Response (Healthy)

| # | srf# | \bar{q} | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil,max}$ | α_{max} |
|----|------|-----------|----------------------------|----------------------|---------------|----------------|
| 1 | 119 | 65.4696 | 38.786 | 2.348 | 3.030 | 32.195 |
| 2 | 253 | 65.4696 | 38.889 | 2.324 | 3.030 | 32.223 |
| 3 | 118 | 65.5666 | 38.787 | 2.393 | 2.956 | 31.228 |
| 4 | 122 | 67.0399 | 38.885 | 2.861 | 3.229 | 34.202 |
| 5 | 256 | 67.0399 | 38.883 | 2.595 | 3.228 | 34.199 |
| 6 | 121 | 67.4267 | 38.885 | 2.974 | 3.142 | 32.943 |
| 7 | 255 | 67.4267 | 38.884 | 2.708 | 3.141 | 32.946 |
| 8 | 124 | 67.6717 | 38.882 | 2.872 | 3.339 | 35.473 |
| 9 | 116 | 68.8746 | 38.886 | 3.108 | 2.928 | 29.624 |
| 10 | 251 | 68.8746 | 38.885 | 2.837 | 2.927 | 29.633 |
| 11 | 115 | 70.9929 | 38.884 | 3.060 | 2.887 | 28.367 |
| 12 | 10 | 74.2746 | 38.867 | 1.090 | 2.987 | 29.458 |
| 13 | 66 | 74.2746 | 38.877 | 2.815 | 2.991 | 28.544 |
| 14 | 202 | 74.2746 | 38.875 | 2.563 | 2.991 | 28.550 |
| 15 | 113 | 75.5664 | 38.876 | 2.880 | 2.886 | 26.879 |
| 16 | 250 | 77.0323 | 38.872 | 2.512 | 2.953 | 27.236 |
| 17 | 258 | 77.2143 | 38.861 | 2.455 | 3.499 | 35.166 |
| 18 | 125 | 77.2914 | 38.859 | 2.673 | 3.635 | 37.464 |
| 19 | 259 | 77.2914 | 38.857 | 2.440 | 3.633 | 37.441 |
| 20 | 37 | 80.2356 | 38.849 | 1.876 | 3.674 | 37.808 |
| 21 | 93 | 80.2356 | 38.850 | 2.633 | 3.688 | 36.964 |
| 22 | 229 | 80.2356 | 38.848 | 2.410 | 3.686 | 36.938 |
| 23 | 15 | 80.3692 | 38.855 | 1.260 | 3.143 | 29.460 |
| 24 | 71 | 80.3692 | 38.861 | 2.712 | 3.148 | 28.535 |
| 25 | 207 | 80.3692 | 38.860 | 2.482 | 3.148 | 28.543 |
| 26 | 33 | 80.5349 | 38.850 | 1.657 | 3.543 | 35.516 |
| 27 | 89 | 80.5349 | 38.852 | 2.597 | 3.555 | 34.632 |
| 28 | 225 | 80.5349 | 38.851 | 2.374 | 3.553 | 34.620 |
| 29 | 28 | 81.4969 | 38.849 | 1.492 | 3.448 | 33.569 |
| 30 | 84 | 81.4969 | 38.852 | 2.567 | 3.457 | 32.682 |
| 31 | 220 | 81.4969 | 38.851 | 2.345 | 3.456 | 32.675 |
| 32 | 1 | 82.2802 | 38.853 | 0.685 | 2.954 | 26.362 |
| 33 | 57 | 82.2802 | 38.860 | 2.210 | 2.957 | 25.459 |
| 34 | 193 | 82.2802 | 38.859 | 1.983 | 2.957 | 25.470 |
| 35 | 7 | 83.3181 | 38.849 | 0.632 | 3.020 | 26.929 |
| 36 | 63 | 83.3181 | 38.857 | 2.081 | 3.023 | 26.030 |
| 37 | 199 | 83.3181 | 38.855 | 1.857 | 3.023 | 26.041 |
| 38 | 19 | 83.4550 | 38.846 | 1.229 | 3.272 | 30.259 |
| 39 | 75 | 83.4550 | 38.851 | 2.531 | 3.277 | 29.351 |
| 40 | 211 | 83.4550 | 38.849 | 2.312 | 3.277 | 29.356 |
| 41 | 25 | 83.7192 | 38.844 | 1.324 | 3.374 | 31.647 |

| # | srf# | \bar{q} | $\delta_{elev(max)}$ | $\delta_{elev(max)}$ | g_{pitmax} | α_{max} |
|----|------|-----------|----------------------|----------------------|--------------|----------------|
| 42 | 81 | 83.7192 | 38.848 | 2.513 | 3.382 | 30.730 |
| 43 | 217 | 83.7192 | 38.847 | 2.296 | 3.381 | 30.729 |
| 44 | 34 | 87.3860 | 38.830 | 1.683 | 3.655 | 34.422 |
| 45 | 90 | 87.3860 | 38.832 | 2.490 | 3.665 | 33.582 |
| 46 | 226 | 87.3860 | 38.830 | 2.288 | 3.664 | 33.565 |
| 47 | 127 | 88.7159 | 38.812 | 2.407 | 4.084 | 36.088 |
| 48 | 261 | 88.7159 | 38.811 | 2.218 | 4.082 | 36.063 |
| 49 | 38 | 89.3983 | 38.822 | 1.998 | 3.834 | 36.415 |
| 50 | 94 | 89.3983 | 38.822 | 2.480 | 3.906 | 34.266 |
| 51 | 230 | 89.3983 | 38.821 | 2.285 | 3.905 | 34.248 |
| 52 | 11 | 91.6970 | 38.826 | 0.131 | 3.191 | 26.806 |
| 53 | 67 | 91.6970 | 38.833 | 1.502 | 3.194 | 25.947 |
| 54 | 203 | 91.6970 | 38.832 | 1.303 | 3.194 | 25.953 |
| 55 | 41 | 94.3473 | 38.791 | 1.710 | 4.180 | 35.844 |
| 56 | 97 | 94.3473 | 38.792 | 2.125 | 4.189 | 35.005 |
| 57 | 233 | 94.3473 | 38.790 | 1.951 | 4.187 | 34.977 |
| 58 | 262 | 101.0962 | 38.741 | 1.687 | 4.507 | 35.655 |
| 59 | 16 | 102.4478 | 38.796 | 0.773 | 3.411 | 26.676 |
| 60 | 72 | 102.4478 | 38.803 | 1.829 | 3.415 | 25.771 |
| 61 | 208 | 102.4478 | 38.801 | 1.655 | 3.415 | 25.768 |
| 62 | 263 | 103.7392 | 38.729 | 1.605 | 4.540 | 39.257 |
| 63 | 42 | 106.1299 | 38.746 | 1.233 | 4.391 | 33.896 |
| 64 | 98 | 106.1299 | 38.748 | 1.694 | 4.368 | 36.489 |
| 65 | 234 | 106.1299 | 38.746 | 1.545 | 4.366 | 36.446 |
| 66 | 264 | 106.4162 | 38.717 | 1.530 | 4.591 | 38.802 |
| 67 | 20 | 109.0025 | 38.777 | 0.730 | 3.602 | 26.773 |
| 68 | 76 | 109.0025 | 38.783 | 1.581 | 3.605 | 25.917 |
| 69 | 212 | 109.0025 | 38.782 | 1.420 | 3.605 | 25.913 |
| 70 | 46 | 109.1273 | 38.704 | 1.043 | 4.605 | 39.470 |
| 71 | 102 | 109.1273 | 38.707 | 1.590 | 4.645 | 38.402 |
| 72 | 238 | 109.1273 | 38.705 | 1.460 | 4.642 | 38.341 |
| 73 | 29 | 110.1905 | 38.770 | 1.019 | 3.885 | 28.810 |
| 74 | 85 | 110.1905 | 38.773 | 1.555 | 3.889 | 27.999 |
| 75 | 221 | 110.1905 | 38.772 | 1.398 | 3.889 | 27.991 |
| 76 | 8 | 110.9265 | 38.777 | -0.217 | 3.309 | 24.275 |
| 77 | 64 | 110.9265 | 38.786 | 1.041 | 3.312 | 23.330 |
| 78 | 200 | 110.9265 | 38.785 | 0.881 | 3.312 | 23.327 |
| 79 | 47 | 111.8726 | 38.692 | 0.772 | 4.647 | 38.745 |
| 80 | 103 | 111.8726 | 38.694 | 1.306 | 4.686 | 37.721 |
| 81 | 239 | 111.8726 | 38.692 | 1.181 | 4.683 | 37.657 |
| 82 | 48 | 114.6519 | 38.679 | 0.537 | 4.688 | 38.050 |

| # | srf# | \bar{q} | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil,max}$ | α_{max} |
|-----|------|-----------|----------------------------|----------------------|---------------|----------------|
| 83 | 104 | 114.6519 | 38.679 | 1.057 | 4.728 | 37.062 |
| 84 | 240 | 114.6519 | 38.677 | 0.938 | 4.725 | 37.000 |
| 85 | 49 | 117.4653 | 38.666 | 0.334 | 4.730 | 37.388 |
| 86 | 105 | 117.4653 | 38.664 | 0.841 | 4.769 | 36.434 |
| 87 | 241 | 117.4653 | 38.662 | 0.727 | 4.766 | 36.372 |
| 88 | 50 | 120.3129 | 38.651 | 0.163 | 4.772 | 36.756 |
| 89 | 106 | 120.3129 | 38.648 | 0.654 | 4.811 | 35.831 |
| 90 | 242 | 120.3129 | 38.646 | 0.545 | 4.808 | 35.769 |
| 91 | 43 | 121.8328 | 38.682 | 0.895 | 4.612 | 35.430 |
| 92 | 99 | 121.8328 | 38.686 | 1.304 | 4.635 | 34.422 |
| 93 | 235 | 121.8328 | 38.684 | 1.185 | 4.633 | 34.383 |
| 94 | 51 | 123.1945 | 38.635 | 0.018 | 4.814 | 36.154 |
| 95 | 107 | 123.1945 | 38.634 | 0.468 | 4.963 | 29.833 |
| 96 | 243 | 123.1945 | 38.631 | 0.362 | 4.962 | 29.802 |
| 97 | 52 | 126.1103 | 38.620 | -0.107 | 4.994 | 30.624 |
| 98 | 108 | 126.1103 | 38.619 | 0.279 | 5.008 | 29.719 |
| 99 | 244 | 126.1103 | 38.617 | 0.177 | 5.007 | 29.688 |
| 100 | 53 | 129.0601 | 38.606 | -0.272 | 5.040 | 30.510 |
| 101 | 109 | 129.0601 | 38.605 | 0.087 | 5.054 | 29.584 |
| 102 | 245 | 129.0601 | 38.602 | -0.012 | 5.053 | 29.555 |
| 103 | 2 | 129.4213 | 38.737 | -0.344 | 3.418 | 22.531 |
| 104 | 58 | 129.4213 | 38.752 | 0.857 | 3.420 | 21.803 |
| 105 | 194 | 129.4213 | 38.750 | 0.719 | 3.420 | 21.794 |
| 106 | 17 | 129.8252 | 38.733 | 0.361 | 3.719 | 25.104 |
| 107 | 73 | 129.8252 | 38.743 | 1.189 | 3.721 | 24.346 |
| 108 | 209 | 129.8252 | 38.741 | 1.054 | 3.721 | 24.334 |
| 109 | 30 | 129.9582 | 38.726 | 0.859 | 4.137 | 28.636 |
| 110 | 86 | 129.9582 | 38.730 | 1.247 | 4.141 | 27.898 |
| 111 | 222 | 129.9582 | 38.728 | 1.116 | 4.141 | 27.881 |
| 112 | 26 | 130.0074 | 38.728 | 0.655 | 3.985 | 27.342 |
| 113 | 82 | 130.0074 | 38.735 | 1.208 | 3.989 | 26.594 |
| 114 | 218 | 130.0074 | 38.733 | 1.075 | 3.989 | 26.580 |
| 115 | 35 | 130.0653 | 38.718 | 1.044 | 4.305 | 30.097 |
| 116 | 91 | 130.0653 | 38.721 | 1.287 | 4.311 | 29.364 |
| 117 | 227 | 130.0653 | 38.719 | 1.158 | 4.310 | 29.344 |
| 118 | 21 | 130.1006 | 38.730 | 0.489 | 3.848 | 26.152 |
| 119 | 77 | 130.1006 | 38.739 | 1.188 | 3.851 | 25.396 |
| 120 | 213 | 130.1006 | 38.737 | 1.054 | 3.851 | 25.385 |
| 121 | 44 | 131.7744 | 38.639 | 0.776 | 4.822 | 27.071 |
| 122 | 100 | 131.7744 | 38.644 | 1.132 | 4.829 | 26.239 |
| 123 | 236 | 131.7744 | 38.642 | 1.026 | 4.828 | 26.218 |

| # | srf# | \bar{q} | $\delta_{elev(max)}$ | $\delta_{elev(max)}$ | g_{pilmax} | α_{max} |
|-----|------|-----------|----------------------|----------------------|--------------|----------------|
| 124 | 54 | 132.0441 | 38.592 | -0.442 | 5.086 | 30.373 |
| 125 | 110 | 132.0441 | 38.590 | -0.108 | 5.099 | 29.429 |
| 126 | 246 | 132.0441 | 38.588 | -0.204 | 5.098 | 29.399 |
| 127 | 39 | 134.8266 | 38.668 | 0.822 | 4.583 | 31.763 |
| 128 | 95 | 134.8266 | 38.671 | 1.114 | 4.616 | 24.882 |
| 129 | 231 | 134.8266 | 38.669 | 1.004 | 4.616 | 24.869 |
| 130 | 55 | 135.0621 | 38.577 | -0.615 | 5.131 | 30.214 |
| 131 | 111 | 135.0621 | 38.576 | -0.306 | 5.144 | 29.247 |
| 132 | 247 | 135.0621 | 38.573 | -0.399 | 5.143 | 29.217 |
| 133 | 56 | 138.1142 | 38.562 | -0.791 | 5.176 | 30.032 |
| 134 | 112 | 138.1142 | 38.561 | -0.507 | 5.188 | 29.042 |
| 135 | 248 | 138.1142 | 38.558 | -0.598 | 5.187 | 29.011 |
| 136 | 45 | 167.7286 | 49.207 | -0.223 | 6.200 | 30.683 |
| 137 | 101 | 167.7286 | 49.212 | 0.013 | 6.197 | 24.225 |
| 138 | 237 | 167.7286 | 49.208 | -0.061 | 6.197 | 24.206 |
| 139 | 22 | 170.3164 | 50.422 | 0.902 | 4.975 | 24.058 |
| 140 | 78 | 170.3164 | 50.431 | 1.285 | 4.977 | 23.377 |
| 141 | 214 | 170.3164 | 50.428 | 1.189 | 4.977 | 23.371 |
| 142 | 40 | 208.2658 | 60.000 | 0.832 | 7.776 | 26.903 |
| 143 | 96 | 208.2658 | 60.000 | 1.047 | 7.778 | 26.042 |
| 144 | 232 | 208.2658 | 60.000 | 0.986 | 7.778 | 26.023 |
| 145 | 31 | 215.9733 | 60.000 | 1.779 | 7.381 | 28.892 |
| 146 | 87 | 215.9733 | 60.000 | 1.953 | 7.383 | 28.083 |
| 147 | 223 | 215.9733 | 60.000 | 1.886 | 7.383 | 28.075 |
| 148 | 126 | 222.8766 | 60.000 | 1.119 | 8.514 | 25.296 |
| 149 | 260 | 222.8766 | 60.000 | 1.063 | 8.514 | 25.275 |
| 150 | 3 | 228.5562 | 60.000 | 1.412 | 6.272 | 24.770 |
| 151 | 59 | 228.5562 | 60.000 | 2.080 | 6.274 | 24.027 |
| 152 | 195 | 228.5562 | 60.000 | 2.007 | 6.274 | 24.022 |
| 153 | 12 | 254.7139 | 60.000 | 1.745 | 7.138 | 25.258 |
| 154 | 68 | 254.7139 | 60.000 | 2.119 | 7.139 | 24.556 |
| 155 | 204 | 254.7139 | 60.000 | 2.055 | 7.139 | 24.550 |
| 156 | 36 | 264.5698 | 60.000 | 1.418 | 8.907 | 24.881 |
| 157 | 92 | 264.5698 | 60.000 | 1.556 | 8.908 | 24.083 |
| 158 | 228 | 264.5698 | 60.000 | 1.507 | 8.908 | 24.065 |
| 159 | 32 | 333.6127 | 60.000 | 1.465 | 9.338 | 20.975 |
| 160 | 88 | 333.6127 | 60.000 | 1.500 | 9.338 | 20.295 |
| 161 | 224 | 333.6127 | 60.000 | 1.460 | 9.338 | 20.280 |
| 162 | 23 | 333.8201 | 60.000 | 2.034 | 8.692 | 23.212 |
| 163 | 79 | 333.8201 | 60.000 | 2.100 | 8.692 | 22.549 |
| 164 | 215 | 333.8201 | 60.000 | 2.056 | 8.692 | 22.540 |

| # | srf# | \bar{q} | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil,max}$ | α_{max} |
|-----|------|-----------|----------------------------|----------------------|---------------|----------------|
| 165 | 123 | 357.0172 | 60.000 | 1.138 | 9.559 | 19.142 |
| 166 | 257 | 357.0172 | 60.000 | 1.101 | 9.559 | 19.128 |
| 167 | 27 | 416.6143 | 60.000 | 1.374 | 9.730 | 18.401 |
| 168 | 83 | 416.6143 | 60.000 | 1.368 | 9.730 | 17.765 |
| 169 | 219 | 416.6143 | 60.000 | 1.336 | 9.730 | 17.752 |
| 170 | 13 | 499.2391 | 60.000 | 1.924 | 9.474 | 18.178 |
| 171 | 69 | 499.2391 | 60.000 | 1.941 | 9.474 | 17.602 |
| 172 | 205 | 499.2391 | 60.000 | 1.911 | 9.474 | 17.594 |
| 173 | 24 | 503.8640 | 60.000 | 1.408 | 10.014 | 16.158 |
| 174 | 80 | 503.8640 | 60.000 | 1.368 | 10.014 | 15.587 |
| 175 | 216 | 503.8640 | 60.000 | 1.341 | 10.014 | 15.576 |
| 176 | 4 | 514.2514 | 60.000 | 1.855 | 9.131 | 17.932 |
| 177 | 60 | 514.2514 | 60.000 | 1.934 | 9.131 | 17.439 |
| 178 | 196 | 514.2514 | 60.000 | 1.903 | 9.131 | 17.433 |
| 179 | 120 | 551.8250 | 60.000 | 0.936 | 10.264 | 13.722 |
| 180 | 254 | 551.8250 | 60.000 | 0.912 | 10.264 | 13.711 |
| 181 | 18 | 618.5337 | 60.000 | 1.320 | 10.326 | 13.819 |
| 182 | 74 | 618.5337 | 60.000 | 1.256 | 10.326 | 13.315 |
| 183 | 210 | 618.5337 | 60.000 | 1.233 | 10.326 | 13.306 |
| 184 | 5 | 699.9532 | 60.000 | 1.744 | 10.059 | 14.277 |
| 185 | 61 | 699.9532 | 60.000 | 1.696 | 10.060 | 13.794 |
| 186 | 197 | 699.9532 | 60.000 | 1.673 | 10.060 | 13.788 |
| 187 | 14 | 771.1717 | 60.000 | 0.746 | 10.646 | 11.383 |
| 188 | 70 | 771.1717 | 60.000 | 0.666 | 10.646 | 10.952 |
| 189 | 206 | 771.1717 | 60.000 | 0.646 | 10.646 | 10.944 |
| 190 | 117 | 825.2729 | 60.000 | 0.333 | 10.791 | 9.910 |
| 191 | 252 | 825.2729 | 60.000 | 0.315 | 10.791 | 9.902 |
| 192 | 9 | 954.4603 | 60.000 | 0.495 | 10.913 | 9.584 |
| 193 | 65 | 954.4603 | 60.000 | 0.399 | 10.913 | 9.201 |
| 194 | 201 | 954.4603 | 60.000 | 0.384 | 10.913 | 9.194 |
| 195 | 6 | 1106.2120 | 60.000 | 0.391 | 11.061 | 8.603 |
| 196 | 62 | 1106.2120 | 60.000 | 0.285 | 11.061 | 8.245 |
| 197 | 198 | 1106.2120 | 60.000 | 0.271 | 11.061 | 8.239 |
| 198 | 114 | 1157.0650 | 60.000 | 0.071 | 11.134 | 7.716 |
| 199 | 249 | 1157.0650 | 60.000 | 0.057 | 11.134 | 7.710 |

C.4 Longitudinal Maximum C_{*cmd} Step Input Time Response (25% Stabilator Failure)

| # | srf# | \bar{q} | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil,max}$ | α_{max} |
|----|------|-----------|----------------------------|----------------------|---------------|----------------|
| 1 | 119 | 65.4696 | 38.924 | 2.590 | 3.036 | 25.921 |
| 2 | 253 | 65.4696 | 38.982 | 2.324 | 3.039 | 25.997 |
| 3 | 118 | 65.5666 | 38.925 | 2.643 | 2.960 | 25.364 |
| 4 | 122 | 67.0399 | 38.979 | 2.861 | 3.243 | 26.903 |
| 5 | 256 | 67.0399 | 38.978 | 2.595 | 3.243 | 26.907 |
| 6 | 121 | 67.4267 | 38.979 | 2.974 | 3.152 | 26.152 |
| 7 | 255 | 67.4267 | 38.978 | 2.708 | 3.151 | 26.160 |
| 8 | 124 | 67.6717 | 38.977 | 2.957 | 3.361 | 27.546 |
| 9 | 116 | 68.8746 | 38.980 | 3.308 | 2.931 | 24.114 |
| 10 | 251 | 68.8746 | 38.979 | 3.043 | 2.930 | 24.126 |
| 11 | 115 | 70.9929 | 38.979 | 3.714 | 2.888 | 23.196 |
| 12 | 10 | 74.2746 | 38.969 | 1.907 | 2.990 | 23.829 |
| 13 | 66 | 74.2746 | 38.974 | 4.168 | 2.994 | 23.025 |
| 14 | 202 | 74.2746 | 38.974 | 3.922 | 2.994 | 23.036 |
| 15 | 113 | 75.5664 | 38.974 | 4.459 | 2.887 | 21.960 |
| 16 | 250 | 77.0323 | 38.971 | 4.126 | 2.954 | 22.066 |
| 17 | 258 | 77.2143 | 38.964 | 3.923 | 3.527 | 26.377 |
| 18 | 125 | 77.2914 | 38.962 | 4.124 | 3.681 | 27.632 |
| 19 | 259 | 77.2914 | 38.961 | 3.889 | 3.679 | 27.622 |
| 20 | 37 | 80.2356 | 38.956 | 3.294 | 3.721 | 27.805 |
| 21 | 93 | 80.2356 | 38.957 | 4.044 | 3.733 | 27.069 |
| 22 | 229 | 80.2356 | 38.956 | 3.819 | 3.731 | 27.058 |
| 23 | 15 | 80.3692 | 38.962 | 2.728 | 3.147 | 23.164 |
| 24 | 71 | 80.3692 | 38.965 | 4.188 | 3.151 | 22.346 |
| 25 | 207 | 80.3692 | 38.964 | 3.956 | 3.151 | 22.359 |
| 26 | 33 | 80.5349 | 38.957 | 3.088 | 3.572 | 26.545 |
| 27 | 89 | 80.5349 | 38.958 | 4.024 | 3.582 | 25.772 |
| 28 | 225 | 80.5349 | 38.958 | 3.799 | 3.581 | 25.770 |
| 29 | 28 | 81.4969 | 38.957 | 2.923 | 3.466 | 25.391 |
| 30 | 84 | 81.4969 | 38.959 | 3.998 | 3.474 | 24.610 |
| 31 | 220 | 81.4969 | 38.958 | 3.774 | 3.473 | 24.613 |
| 32 | 1 | 82.2802 | 38.961 | 2.134 | 2.954 | 21.300 |
| 33 | 57 | 82.2802 | 38.965 | 3.668 | 2.956 | 20.511 |
| 34 | 193 | 82.2802 | 38.964 | 3.439 | 2.957 | 20.524 |
| 35 | 7 | 83.3181 | 38.959 | 2.066 | 3.021 | 21.559 |
| 36 | 63 | 83.3181 | 38.963 | 3.522 | 3.023 | 20.776 |
| 37 | 199 | 83.3181 | 38.962 | 3.297 | 3.023 | 20.790 |
| 38 | 19 | 83.4550 | 38.956 | 2.658 | 3.279 | 23.387 |
| 39 | 75 | 83.4550 | 38.959 | 3.966 | 3.283 | 22.587 |
| 40 | 211 | 83.4550 | 38.958 | 3.745 | 3.283 | 22.598 |
| 41 | 25 | 83.7191 | 38.954 | 2.741 | 3.385 | 24.145 |

| # | srf# | \bar{q} | $\dot{\delta}_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil_{max}}$ | α_{max} |
|----|------|-----------|----------------------------|----------------------|-----------------|----------------|
| 42 | 81 | 83.7191 | 38.957 | 3.931 | 3.392 | 23.344 |
| 43 | 217 | 83.7191 | 38.956 | 3.712 | 3.391 | 23.351 |
| 44 | 34 | 87.3860 | 38.945 | 3.031 | 3.682 | 25.348 |
| 45 | 90 | 87.3860 | 38.946 | 3.834 | 3.691 | 24.619 |
| 46 | 226 | 87.3860 | 38.945 | 3.629 | 3.690 | 24.615 |
| 47 | 127 | 88.7159 | 38.933 | 3.593 | 4.130 | 25.626 |
| 48 | 261 | 88.7159 | 38.932 | 3.402 | 4.129 | 25.618 |
| 49 | 38 | 89.3983 | 38.939 | 3.302 | 3.879 | 26.209 |
| 50 | 94 | 89.3983 | 38.940 | 3.704 | 3.932 | 24.607 |
| 51 | 230 | 89.3983 | 38.939 | 3.507 | 3.932 | 24.605 |
| 52 | 11 | 91.6970 | 38.945 | 1.476 | 3.192 | 20.995 |
| 53 | 67 | 91.6970 | 38.948 | 2.858 | 3.195 | 20.240 |
| 54 | 203 | 91.6970 | 38.948 | 2.657 | 3.195 | 20.250 |
| 55 | 41 | 94.3473 | 38.920 | 2.833 | 4.226 | 25.318 |
| 56 | 97 | 94.3473 | 38.920 | 3.245 | 4.231 | 24.646 |
| 57 | 233 | 94.3473 | 38.919 | 3.068 | 4.230 | 24.635 |
| 58 | 262 | 101.0962 | 38.887 | 2.676 | 4.569 | 24.474 |
| 59 | 16 | 102.4478 | 38.926 | 1.992 | 3.413 | 20.064 |
| 60 | 72 | 102.4478 | 38.930 | 3.051 | 3.416 | 19.299 |
| 61 | 208 | 102.4478 | 38.929 | 2.875 | 3.416 | 19.303 |
| 62 | 263 | 103.7392 | 38.880 | 2.523 | 4.633 | 26.200 |
| 63 | 42 | 106.1299 | 38.891 | 2.230 | 4.427 | 23.554 |
| 64 | 98 | 106.1299 | 38.892 | 2.688 | 4.425 | 24.735 |
| 65 | 234 | 106.1299 | 38.891 | 2.536 | 4.424 | 24.714 |
| 66 | 264 | 106.4162 | 38.872 | 2.391 | 4.681 | 25.768 |
| 67 | 20 | 109.0025 | 38.914 | 1.877 | 3.604 | 19.744 |
| 68 | 76 | 109.0025 | 38.917 | 2.729 | 3.606 | 19.031 |
| 69 | 212 | 109.0025 | 38.916 | 2.566 | 3.606 | 19.035 |
| 70 | 46 | 109.1273 | 38.864 | 1.869 | 4.703 | 26.233 |
| 71 | 102 | 109.1273 | 38.866 | 2.402 | 4.730 | 25.371 |
| 72 | 238 | 109.1273 | 38.864 | 2.265 | 4.728 | 25.337 |
| 73 | 29 | 110.1905 | 38.908 | 2.109 | 3.891 | 20.707 |
| 74 | 85 | 110.1905 | 38.910 | 2.643 | 3.894 | 20.050 |
| 75 | 221 | 110.1905 | 38.909 | 2.485 | 3.894 | 20.052 |
| 76 | 8 | 110.9265 | 38.915 | 0.973 | 3.310 | 18.464 |
| 77 | 64 | 110.9265 | 38.920 | 2.235 | 3.312 | 17.663 |
| 78 | 200 | 110.9265 | 38.919 | 2.073 | 3.312 | 17.667 |
| 79 | 47 | 111.8726 | 38.856 | 1.554 | 4.739 | 25.660 |
| 80 | 103 | 111.8726 | 38.857 | 2.068 | 4.768 | 24.837 |
| 81 | 239 | 111.8726 | 38.856 | 1.937 | 4.766 | 24.801 |
| 82 | 48 | 114.6519 | 38.848 | 1.275 | 4.775 | 25.104 |

| # | srf# | \bar{q} | $\delta_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil_{max}}$ | α_{max} |
|-----|------|-----------|----------------------|----------------------|-----------------|----------------|
| 83 | 104 | 114.6519 | 38.848 | 1.769 | 4.806 | 24.313 |
| 84 | 240 | 114.6519 | 38.846 | 1.643 | 4.804 | 24.277 |
| 85 | 49 | 117.4653 | 38.839 | 1.026 | 4.811 | 24.568 |
| 86 | 105 | 117.4653 | 38.838 | 1.501 | 4.844 | 23.804 |
| 87 | 241 | 117.4653 | 38.836 | 1.381 | 4.841 | 23.769 |
| 88 | 50 | 120.3129 | 38.829 | 0.805 | 4.847 | 24.050 |
| 89 | 106 | 120.3129 | 38.827 | 1.261 | 4.881 | 23.311 |
| 90 | 242 | 120.3129 | 38.826 | 1.145 | 4.878 | 23.274 |
| 91 | 43 | 121.8328 | 38.850 | 1.653 | 4.663 | 23.511 |
| 92 | 99 | 121.8328 | 38.852 | 2.052 | 4.678 | 22.698 |
| 93 | 235 | 121.8328 | 38.850 | 1.927 | 4.677 | 22.679 |
| 94 | 51 | 123.1945 | 38.819 | 0.608 | 4.882 | 23.552 |
| 95 | 107 | 123.1945 | 38.818 | 0.984 | 4.978 | 19.843 |
| 96 | 243 | 123.1945 | 38.816 | 0.873 | 4.978 | 19.831 |
| 97 | 52 | 126.1103 | 38.808 | 0.384 | 5.016 | 20.387 |
| 98 | 108 | 126.1103 | 38.808 | 0.749 | 5.023 | 19.652 |
| 99 | 244 | 126.1103 | 38.807 | 0.641 | 5.023 | 19.639 |
| 100 | 53 | 129.0601 | 38.799 | 0.175 | 5.061 | 20.196 |
| 101 | 109 | 129.0601 | 38.798 | 0.514 | 5.067 | 19.447 |
| 102 | 245 | 129.0601 | 38.797 | 0.409 | 5.067 | 19.434 |
| 103 | 2 | 129.4213 | 38.891 | 0.759 | 3.418 | 16.762 |
| 104 | 58 | 129.4213 | 38.899 | 1.968 | 3.420 | 16.081 |
| 105 | 194 | 129.4213 | 38.898 | 1.828 | 3.420 | 16.081 |
| 106 | 17 | 129.8252 | 38.886 | 1.410 | 3.721 | 18.012 |
| 107 | 73 | 129.8252 | 38.892 | 2.245 | 3.723 | 17.351 |
| 108 | 209 | 129.8252 | 38.891 | 2.108 | 3.723 | 17.351 |
| 109 | 30 | 129.9582 | 38.879 | 1.840 | 4.146 | 19.818 |
| 110 | 86 | 129.9582 | 38.881 | 2.227 | 4.149 | 19.202 |
| 111 | 222 | 129.9582 | 38.880 | 2.094 | 4.148 | 19.199 |
| 112 | 26 | 130.0074 | 38.881 | 1.661 | 3.991 | 19.161 |
| 113 | 82 | 130.0074 | 38.885 | 2.216 | 3.994 | 18.525 |
| 114 | 218 | 130.0074 | 38.884 | 2.081 | 3.993 | 18.525 |
| 115 | 35 | 130.0653 | 38.873 | 1.989 | 4.319 | 20.535 |
| 116 | 91 | 130.0653 | 38.875 | 2.228 | 4.323 | 19.936 |
| 117 | 227 | 130.0653 | 38.873 | 2.097 | 4.322 | 19.931 |
| 118 | 21 | 130.1006 | 38.884 | 1.517 | 3.851 | 18.544 |
| 119 | 77 | 130.1006 | 38.889 | 2.220 | 3.854 | 17.893 |
| 120 | 213 | 130.1006 | 38.888 | 2.085 | 3.854 | 17.893 |
| 121 | 44 | 131.7744 | 38.821 | 1.356 | 4.829 | 18.476 |
| 122 | 100 | 131.7744 | 38.824 | 1.704 | 4.832 | 17.803 |
| 123 | 236 | 131.7744 | 38.823 | 1.592 | 4.832 | 17.797 |

| # | srf# | \bar{q} | $\delta_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil_{max}}$ | α_{max} |
|-----|------|-----------|----------------------|----------------------|-----------------|----------------|
| 124 | 54 | 132.0441 | 38.789 | -0.036 | 5.106 | 19.989 |
| 125 | 110 | 132.0441 | 38.788 | 0.278 | 5.111 | 19.228 |
| 126 | 246 | 132.0441 | 38.787 | 0.177 | 5.111 | 19.215 |
| 127 | 39 | 134.8266 | 38.840 | 1.549 | 4.606 | 21.099 |
| 128 | 95 | 134.8266 | 38.842 | 1.804 | 4.617 | 17.085 |
| 129 | 231 | 134.8266 | 38.841 | 1.689 | 4.617 | 17.084 |
| 130 | 55 | 135.0621 | 38.779 | -0.248 | 5.150 | 19.768 |
| 131 | 111 | 135.0621 | 38.778 | 0.042 | 5.154 | 18.992 |
| 132 | 247 | 135.0621 | 38.777 | -0.057 | 5.154 | 18.979 |
| 133 | 56 | 138.1142 | 38.769 | -0.461 | 5.193 | 19.533 |
| 134 | 112 | 138.1142 | 38.768 | -0.195 | 5.197 | 18.742 |
| 135 | 248 | 138.1142 | 38.767 | -0.291 | 5.197 | 18.728 |
| 136 | 45 | 167.7286 | 49.503 | 0.004 | 6.202 | 19.367 |
| 137 | 101 | 167.7286 | 49.507 | 0.287 | 6.195 | 15.983 |
| 138 | 237 | 167.7286 | 49.504 | 0.208 | 6.194 | 15.978 |
| 139 | 22 | 170.3164 | 50.659 | 1.823 | 4.975 | 16.270 |
| 140 | 78 | 170.3164 | 50.664 | 2.209 | 4.975 | 15.738 |
| 141 | 214 | 170.3164 | 50.662 | 2.106 | 4.976 | 15.743 |
| 142 | 40 | 208.2658 | 60.000 | 1.027 | 7.773 | 17.328 |
| 143 | 96 | 208.2658 | 60.000 | 1.242 | 7.777 | 16.673 |
| 144 | 232 | 208.2658 | 60.000 | 1.181 | 7.777 | 16.672 |
| 145 | 31 | 215.9733 | 60.000 | 2.203 | 7.381 | 18.575 |
| 146 | 87 | 215.9733 | 60.000 | 2.368 | 7.383 | 17.954 |
| 147 | 223 | 215.9733 | 60.000 | 2.293 | 7.383 | 17.962 |
| 148 | 126 | 222.8766 | 60.000 | 1.316 | 8.513 | 16.129 |
| 149 | 260 | 222.8766 | 60.000 | 1.260 | 8.513 | 16.128 |
| 150 | 3 | 228.5562 | 60.000 | 2.553 | 6.272 | 16.301 |
| 151 | 59 | 228.5562 | 60.000 | 3.244 | 6.274 | 15.711 |
| 152 | 195 | 228.5562 | 60.000 | 3.165 | 6.274 | 15.721 |
| 153 | 12 | 254.7139 | 60.000 | 2.441 | 7.138 | 16.299 |
| 154 | 68 | 254.7139 | 60.000 | 2.816 | 7.139 | 15.764 |
| 155 | 204 | 254.7139 | 60.000 | 2.745 | 7.139 | 15.774 |
| 156 | 36 | 264.5698 | 60.000 | 1.611 | 8.906 | 15.821 |
| 157 | 92 | 264.5698 | 60.000 | 1.748 | 8.908 | 15.208 |
| 158 | 228 | 264.5698 | 60.000 | 1.700 | 8.908 | 15.208 |
| 159 | 32 | 333.6127 | 60.000 | 1.634 | 9.338 | 13.294 |
| 160 | 88 | 333.6127 | 60.000 | 1.667 | 9.338 | 12.768 |
| 161 | 224 | 333.6127 | 60.000 | 1.627 | 9.338 | 12.768 |
| 162 | 23 | 333.8201 | 60.000 | 2.220 | 8.692 | 14.619 |
| 163 | 79 | 333.8201 | 60.000 | 2.284 | 8.692 | 14.111 |
| 164 | 215 | 333.8201 | 60.000 | 2.241 | 8.692 | 14.116 |

| # | srf# | \bar{q} | $\delta_{elev(max)}$ | $\delta_{elev(max)}$ | $g_{pil,max}$ | α_{max} |
|-----|------|-----------|----------------------|----------------------|---------------|----------------|
| 165 | 123 | 357.0172 | 60.000 | 1.304 | 9.559 | 12.037 |
| 166 | 257 | 357.0172 | 60.000 | 1.268 | 9.559 | 12.038 |
| 167 | 27 | 416.6143 | 60.000 | 1.532 | 9.730 | 11.608 |
| 168 | 83 | 416.6143 | 60.000 | 1.526 | 9.730 | 11.112 |
| 169 | 219 | 416.6143 | 60.000 | 1.494 | 9.730 | 11.113 |
| 170 | 13 | 499.2391 | 60.000 | 2.078 | 9.474 | 11.343 |
| 171 | 69 | 499.2391 | 60.000 | 2.093 | 9.474 | 10.902 |
| 172 | 205 | 499.2391 | 60.000 | 2.063 | 9.474 | 10.906 |
| 173 | 24 | 503.8640 | 60.000 | 1.540 | 10.014 | 10.162 |
| 174 | 80 | 503.8640 | 60.000 | 1.499 | 10.014 | 9.713 |
| 175 | 216 | 503.8640 | 60.000 | 1.472 | 10.014 | 9.714 |
| 176 | 4 | 514.2514 | 60.000 | 2.004 | 9.131 | 11.218 |
| 177 | 60 | 514.2514 | 60.000 | 2.082 | 9.131 | 10.851 |
| 178 | 196 | 514.2514 | 60.000 | 2.051 | 9.131 | 10.857 |
| 179 | 120 | 551.8250 | 60.000 | 1.052 | 10.264 | 8.591 |
| 180 | 254 | 551.8250 | 60.000 | 1.028 | 10.264 | 8.591 |
| 181 | 18 | 618.5337 | 60.000 | 1.436 | 10.326 | 8.675 |
| 182 | 74 | 618.5337 | 60.000 | 1.368 | 10.326 | 8.276 |
| 183 | 210 | 618.5337 | 60.000 | 1.346 | 10.326 | 8.277 |
| 184 | 5 | 699.9532 | 60.000 | 1.854 | 10.059 | 8.856 |
| 185 | 61 | 699.9532 | 60.000 | 1.804 | 10.060 | 8.485 |
| 186 | 197 | 699.9532 | 60.000 | 1.781 | 10.060 | 8.488 |
| 187 | 14 | 771.1717 | 60.000 | 0.855 | 10.646 | 7.176 |
| 188 | 70 | 771.1717 | 60.000 | 0.771 | 10.646 | 6.830 |
| 189 | 206 | 771.1717 | 60.000 | 0.752 | 10.646 | 6.831 |
| 190 | 117 | 825.2729 | 60.000 | 0.435 | 10.791 | 6.213 |
| 191 | 252 | 825.2729 | 60.000 | 0.417 | 10.791 | 6.213 |
| 192 | 9 | 954.4603 | 60.000 | 0.580 | 10.913 | 6.053 |
| 193 | 65 | 954.4603 | 60.000 | 0.484 | 10.913 | 5.742 |
| 194 | 201 | 954.4603 | 60.000 | 0.467 | 10.913 | 5.741 |
| 195 | 6 | 1106.2120 | 60.000 | 0.475 | 11.061 | 5.436 |
| 196 | 62 | 1106.2120 | 60.000 | 0.364 | 11.061 | 5.142 |
| 197 | 198 | 1106.2120 | 60.000 | 0.351 | 11.061 | 5.142 |
| 198 | 114 | 1157.0650 | 60.000 | 0.150 | 11.134 | 4.833 |
| 199 | 249 | 1157.0650 | 60.000 | 0.137 | 11.134 | 4.833 |

C.5 Longitudinal Channel Disturbance Time Response

| # | srf# | \bar{q} | t_{settle} | $Dist_{max}$ |
|----|------|-----------|--------------|--------------|
| 1 | 119 | 65.4696 | 1.155 | 0.087 |
| 2 | 253 | 65.4696 | 1.140 | 0.197 |
| 3 | 118 | 65.5666 | 1.155 | 0.084 |
| 4 | 122 | 67.0399 | 1.130 | 0.198 |
| 5 | 256 | 67.0399 | 1.120 | 0.197 |
| 6 | 121 | 67.4267 | 1.135 | 0.209 |
| 7 | 255 | 67.4267 | 1.130 | 0.209 |
| 8 | 124 | 67.6717 | 1.120 | 0.196 |
| 9 | 116 | 68.8746 | 1.155 | 0.237 |
| 10 | 251 | 68.8746 | 1.155 | 0.236 |
| 11 | 115 | 70.9929 | 1.160 | 0.259 |
| 12 | 10 | 74.2746 | 1.140 | 0.247 |
| 13 | 66 | 74.2746 | 1.150 | 0.285 |
| 14 | 202 | 74.2746 | 1.150 | 0.284 |
| 15 | 113 | 75.5664 | 1.170 | 0.302 |
| 16 | 250 | 77.0323 | 1.160 | 0.313 |
| 17 | 258 | 77.2143 | 1.145 | 0.298 |
| 18 | 125 | 77.2914 | 1.135 | 0.293 |
| 19 | 259 | 77.2914 | 1.130 | 0.292 |
| 20 | 37 | 80.2356 | 1.120 | 0.288 |
| 21 | 93 | 80.2356 | 1.130 | 0.318 |
| 22 | 229 | 80.2356 | 1.125 | 0.317 |
| 23 | 15 | 80.3692 | 1.160 | 0.308 |
| 24 | 71 | 80.3692 | 1.170 | 0.327 |
| 25 | 207 | 80.3692 | 1.165 | 0.326 |
| 26 | 33 | 80.5349 | 1.135 | 0.293 |
| 27 | 89 | 80.5349 | 1.145 | 0.321 |
| 28 | 225 | 80.5349 | 1.140 | 0.320 |
| 29 | 28 | 81.4969 | 1.145 | 0.302 |
| 30 | 84 | 81.4969 | 1.150 | 0.327 |
| 31 | 220 | 81.4969 | 1.150 | 0.327 |
| 32 | 1 | 82.2802 | 1.165 | 0.317 |
| 33 | 57 | 82.2802 | 1.170 | 0.333 |
| 34 | 193 | 82.2802 | 1.170 | 0.332 |
| 35 | 7 | 83.3181 | 1.165 | 0.317 |
| 36 | 63 | 83.3181 | 1.170 | 0.335 |
| 37 | 199 | 83.3181 | 1.170 | 0.334 |
| 38 | 19 | 83.4550 | 1.150 | 0.313 |
| 39 | 75 | 83.4550 | 1.160 | 0.336 |
| 40 | 211 | 83.4550 | 1.160 | 0.336 |
| 41 | 25 | 83.7191 | 1.145 | 0.313 |

| # | srf# | \bar{q} | t_{settle} | $Dist_{max}$ |
|----|------|-----------|--------------|--------------|
| 42 | 81 | 83.7191 | 1.155 | 0.338 |
| 43 | 217 | 83.7191 | 1.150 | 0.337 |
| 44 | 34 | 87.3860 | 1.125 | 0.339 |
| 45 | 90 | 87.3860 | 1.135 | 0.370 |
| 46 | 226 | 87.3860 | 1.130 | 0.369 |
| 47 | 127 | 88.7159 | 1.200 | 0.404 |
| 48 | 261 | 88.7159 | 1.200 | 0.403 |
| 49 | 38 | 89.3983 | 1.110 | 0.366 |
| 50 | 94 | 89.3983 | 1.220 | 0.412 |
| 51 | 230 | 89.3983 | 1.210 | 0.411 |
| 52 | 11 | 91.6970 | 1.155 | 0.333 |
| 53 | 67 | 91.6970 | 1.160 | 0.356 |
| 54 | 203 | 91.6970 | 1.165 | 0.355 |
| 55 | 41 | 94.3473 | 1.190 | 0.401 |
| 56 | 97 | 94.3473 | 1.190 | 0.420 |
| 57 | 233 | 94.3473 | 1.190 | 0.419 |
| 58 | 262 | 101.0962 | 1.140 | 0.413 |
| 59 | 16 | 102.4478 | 1.170 | 0.364 |
| 60 | 72 | 102.4478 | 1.170 | 0.378 |
| 61 | 208 | 102.4478 | 1.165 | 0.377 |
| 62 | 263 | 103.7392 | 1.235 | 0.435 |
| 63 | 42 | 106.1299 | 1.175 | 0.429 |
| 64 | 98 | 106.1299 | 1.210 | 0.455 |
| 65 | 234 | 106.1299 | 1.205 | 0.454 |
| 66 | 264 | 106.4162 | 1.230 | 0.450 |
| 67 | 20 | 109.0025 | 1.165 | 0.384 |
| 68 | 76 | 109.0025 | 1.170 | 0.401 |
| 69 | 212 | 109.0025 | 1.170 | 0.400 |
| 70 | 46 | 109.1273 | 1.195 | 0.425 |
| 71 | 102 | 109.1273 | 1.235 | 0.466 |
| 72 | 238 | 109.1273 | 1.230 | 0.465 |
| 73 | 29 | 110.1905 | 1.180 | 0.428 |
| 74 | 85 | 110.1905 | 1.185 | 0.448 |
| 75 | 221 | 110.1905 | 1.180 | 0.447 |
| 76 | 8 | 110.9265 | 1.160 | 0.347 |
| 77 | 64 | 110.9265 | 1.160 | 0.359 |
| 78 | 200 | 110.9265 | 1.160 | 0.358 |
| 79 | 47 | 111.8726 | 1.175 | 0.435 |
| 80 | 103 | 111.8726 | 1.215 | 0.477 |
| 81 | 239 | 111.8726 | 1.205 | 0.476 |
| 82 | 48 | 114.6519 | 1.150 | 0.449 |

| # | srf# | \bar{q} | t_{settle} | $Dist_{max}$ |
|-----|------|-----------|--------------|--------------|
| 83 | 104 | 114.6519 | 1.190 | 0.491 |
| 84 | 240 | 114.6519 | 1.190 | 0.491 |
| 85 | 49 | 117.4653 | 1.140 | 0.465 |
| 86 | 105 | 117.4653 | 1.180 | 0.508 |
| 87 | 241 | 117.4653 | 1.170 | 0.507 |
| 88 | 50 | 120.3129 | 1.120 | 0.483 |
| 89 | 106 | 120.3129 | 1.160 | 0.527 |
| 90 | 242 | 120.3129 | 1.155 | 0.526 |
| 91 | 43 | 121.8328 | 1.190 | 0.490 |
| 92 | 99 | 121.8328 | 1.215 | 0.526 |
| 93 | 235 | 121.8328 | 1.210 | 0.525 |
| 94 | 51 | 123.1945 | 1.110 | 0.503 |
| 95 | 107 | 123.1945 | 1.220 | 0.558 |
| 96 | 243 | 123.1945 | 1.215 | 0.556 |
| 97 | 52 | 126.1103 | 1.200 | 0.541 |
| 98 | 108 | 126.1103 | 1.225 | 0.570 |
| 99 | 244 | 126.1103 | 1.220 | 0.569 |
| 100 | 53 | 129.0601 | 1.205 | 0.553 |
| 101 | 109 | 129.0601 | 1.230 | 0.583 |
| 102 | 245 | 129.0601 | 1.235 | 0.581 |
| 103 | 2 | 129.4213 | 1.155 | 0.343 |
| 104 | 58 | 129.4213 | 1.160 | 0.358 |
| 105 | 194 | 129.4213 | 1.155 | 0.357 |
| 106 | 17 | 129.8252 | 1.160 | 0.399 |
| 107 | 73 | 129.8252 | 1.160 | 0.419 |
| 108 | 209 | 129.8252 | 1.160 | 0.417 |
| 109 | 30 | 129.9582 | 1.165 | 0.495 |
| 110 | 86 | 129.9582 | 1.170 | 0.520 |
| 111 | 222 | 129.9582 | 1.170 | 0.519 |
| 112 | 26 | 130.0074 | 1.165 | 0.458 |
| 113 | 82 | 130.0074 | 1.170 | 0.481 |
| 114 | 218 | 130.0074 | 1.165 | 0.479 |
| 115 | 35 | 130.0653 | 1.175 | 0.534 |
| 116 | 91 | 130.0653 | 1.175 | 0.560 |
| 117 | 227 | 130.0653 | 1.175 | 0.559 |
| 118 | 21 | 130.1006 | 1.160 | 0.426 |
| 119 | 77 | 130.1006 | 1.160 | 0.448 |
| 120 | 213 | 130.1006 | 1.160 | 0.446 |
| 121 | 44 | 131.7744 | 1.160 | 0.532 |
| 122 | 100 | 131.7744 | 1.175 | 0.564 |
| 123 | 236 | 131.7744 | 1.170 | 0.563 |

| # | srf# | \bar{q} | t_{settle} | $Dist_{max}$ |
|-----|------|-----------|--------------|--------------|
| 124 | 54 | 132.0441 | 1.220 | 0.566 |
| 125 | 110 | 132.0441 | 1.240 | 0.595 |
| 126 | 246 | 132.0441 | 1.240 | 0.594 |
| 127 | 39 | 134.8266 | 1.185 | 0.541 |
| 128 | 95 | 134.8266 | 1.160 | 0.579 |
| 129 | 231 | 134.8266 | 1.160 | 0.578 |
| 130 | 55 | 135.0621 | 1.220 | 0.579 |
| 131 | 111 | 135.0621 | 1.245 | 0.609 |
| 132 | 247 | 135.0621 | 1.245 | 0.607 |
| 133 | 56 | 138.1142 | 1.230 | 0.592 |
| 134 | 112 | 138.1142 | 1.250 | 0.622 |
| 135 | 248 | 138.1142 | 1.245 | 0.621 |
| 136 | 45 | 167.7286 | 1.190 | 0.640 |
| 137 | 101 | 167.7286 | 1.095 | 0.630 |
| 138 | 237 | 167.7286 | 1.100 | 0.628 |
| 139 | 22 | 170.3164 | 1.100 | 0.545 |
| 140 | 78 | 170.3164 | 1.095 | 0.570 |
| 141 | 214 | 170.3164 | 1.095 | 0.568 |
| 142 | 40 | 208.2658 | 1.155 | 0.633 |
| 143 | 96 | 208.2658 | 1.115 | 0.661 |
| 144 | 232 | 208.2658 | 1.120 | 0.659 |
| 145 | 31 | 215.9733 | 1.095 | 0.624 |
| 146 | 87 | 215.9733 | 1.085 | 0.645 |
| 147 | 223 | 215.9733 | 1.090 | 0.643 |
| 148 | 126 | 222.8766 | 1.170 | 0.685 |
| 149 | 260 | 222.8766 | 1.190 | 0.683 |
| 150 | 3 | 228.5562 | 1.145 | 0.497 |
| 151 | 59 | 228.5562 | 1.120 | 0.529 |
| 152 | 195 | 228.5562 | 1.130 | 0.527 |
| 153 | 12 | 254.7139 | 1.100 | 0.586 |
| 154 | 68 | 254.7139 | 1.085 | 0.610 |
| 155 | 204 | 254.7139 | 1.090 | 0.608 |
| 156 | 36 | 264.5698 | 1.250 | 0.666 |
| 157 | 92 | 264.5698 | 1.135 | 0.697 |
| 158 | 228 | 264.5698 | 1.145 | 0.695 |
| 159 | 32 | 333.6127 | 1.430 | 0.697 |
| 160 | 88 | 333.6127 | 1.155 | 0.730 |
| 161 | 224 | 333.6127 | 1.180 | 0.728 |
| 162 | 23 | 333.8201 | 1.070 | 0.656 |
| 163 | 79 | 333.8201 | 1.040 | 0.678 |
| 164 | 215 | 333.8201 | 1.045 | 0.676 |

| # | srf# | \bar{q} | t_{settle} | $Dist_{max}$ |
|-----|------|-----------|--------------|--------------|
| 165 | 123 | 357.0172 | 1.295 | 0.758 |
| 166 | 257 | 357.0172 | 1.375 | 0.755 |
| 167 | 27 | 416.6143 | 4.805 | 0.721 |
| 168 | 83 | 416.6143 | 1.210 | 0.754 |
| 169 | 219 | 416.6143 | 1.260 | 0.751 |
| 170 | 13 | 499.2391 | 1.110 | 0.676 |
| 171 | 69 | 499.2391 | 1.040 | 0.699 |
| 172 | 205 | 499.2391 | 1.060 | 0.696 |
| 173 | 24 | 503.8640 | 4.830 | 0.734 |
| 174 | 80 | 503.8640 | 1.235 | 0.768 |
| 175 | 216 | 503.8640 | 1.290 | 0.765 |
| 176 | 4 | 514.2514 | 1.105 | 0.662 |
| 177 | 60 | 514.2514 | 1.080 | 0.673 |
| 178 | 196 | 514.2514 | 1.095 | 0.671 |
| 179 | 120 | 551.8250 | 4.845 | 0.806 |
| 180 | 254 | 551.8250 | 4.845 | 0.804 |
| 181 | 18 | 618.5337 | 4.855 | 0.759 |
| 182 | 74 | 618.5337 | 1.400 | 0.794 |
| 183 | 210 | 618.5337 | 1.530 | 0.791 |
| 184 | 5 | 699.9532 | 1.165 | 0.697 |
| 185 | 61 | 699.9532 | 1.055 | 0.721 |
| 186 | 197 | 699.9532 | 1.080 | 0.719 |
| 187 | 14 | 771.1717 | 4.890 | 0.801 |
| 188 | 70 | 771.1717 | 4.885 | 0.836 |
| 189 | 206 | 771.1717 | 4.885 | 0.835 |

Appendix D. Lateral Channel Time Response

| Variable | Units |
|-----------------------|------------|
| \bar{q} | lbs/ft^2 |
| t_1 | seconds |
| ϕ | degrees |
| β | degrees |
| $\dot{\delta}_{ail}$ | deg/sec |
| δ_{ail} | degrees |
| $\dot{\delta}_{rud}$ | deg/sec |
| δ_{rud} | degrees |
| $\dot{\delta}_{elev}$ | deg/sec |
| δ_{elev} | degrees |

D.1 Lateral Unit P_{cmd} Step Input Time Response (Healthy)

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\dot{\delta}_{a_{max}}$ | $\delta_{r_{max}}$ | $\dot{\delta}_{r_{max}}$ | $\delta_{elev_{max}}$ | $\dot{\delta}_{elev_{max}}$ |
|----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------------|--------------------|--------------------------|-----------------------|-----------------------------|
| 1 | 119 | 65.4696 | 0.224 | 1.917 | 0.056 | 0.414 | 0.266 | 0.462 | 0.400 | 0.122 | 0.078 |
| 2 | 253 | 65.4696 | 0.224 | 1.918 | 0.056 | 0.414 | 0.265 | 0.461 | 0.399 | 0.122 | 0.078 |
| 3 | 118 | 65.5666 | 0.224 | 1.893 | 0.057 | 0.414 | 0.270 | 0.462 | 0.452 | 0.122 | 0.079 |
| 4 | 122 | 67.0399 | 0.228 | 1.974 | 0.052 | 0.414 | 0.253 | 0.446 | 0.314 | 0.122 | 0.074 |
| 5 | 256 | 67.0399 | 0.227 | 1.975 | 0.052 | 0.414 | 0.253 | 0.446 | 0.313 | 0.122 | 0.074 |
| 6 | 121 | 67.4267 | 0.229 | 1.957 | 0.053 | 0.414 | 0.254 | 0.447 | 0.334 | 0.122 | 0.075 |
| 7 | 255 | 67.4267 | 0.229 | 1.957 | 0.053 | 0.414 | 0.254 | 0.447 | 0.333 | 0.122 | 0.075 |
| 8 | 124 | 67.6717 | 0.228 | 1.998 | 0.051 | 0.414 | 0.249 | 0.438 | 0.294 | 0.122 | 0.073 |
| 9 | 116 | 68.8746 | 0.233 | 1.902 | 0.054 | 0.414 | 0.260 | 0.444 | 0.466 | 0.122 | 0.076 |
| 10 | 251 | 68.8746 | 0.233 | 1.902 | 0.054 | 0.414 | 0.260 | 0.444 | 0.464 | 0.122 | 0.076 |
| 11 | 115 | 70.9929 | 0.238 | 1.894 | 0.053 | 0.414 | 0.257 | 0.432 | 0.492 | 0.122 | 0.075 |
| 12 | 10 | 74.2746 | 0.243 | 1.893 | 0.052 | 0.413 | 0.256 | 0.445 | 0.432 | 0.122 | 0.075 |
| 13 | 66 | 74.2746 | 0.247 | 1.945 | 0.050 | 0.414 | 0.239 | 0.416 | 0.409 | 0.122 | 0.070 |
| 14 | 202 | 74.2746 | 0.247 | 1.945 | 0.050 | 0.414 | 0.239 | 0.416 | 0.408 | 0.122 | 0.070 |
| 15 | 113 | 75.5664 | 0.248 | 1.907 | 0.050 | 0.414 | 0.245 | 0.407 | 0.478 | 0.122 | 0.072 |
| 16 | 250 | 77.0323 | 0.252 | 1.936 | 0.048 | 0.413 | 0.235 | 0.401 | 0.426 | 0.122 | 0.069 |
| 17 | 258 | 77.2143 | 0.248 | 2.047 | 0.042 | 0.414 | 0.221 | 0.382 | 0.224 | 0.122 | 0.065 |
| 18 | 125 | 77.2914 | 0.247 | 2.069 | 0.041 | 0.414 | 0.219 | 0.377 | 0.218 | 0.122 | 0.064 |
| 19 | 259 | 77.2914 | 0.247 | 2.070 | 0.041 | 0.414 | 0.219 | 0.377 | 0.217 | 0.122 | 0.064 |
| 20 | 37 | 80.2356 | 0.255 | 2.066 | 0.041 | 0.413 | 0.217 | 0.389 | 0.216 | 0.122 | 0.064 |
| 21 | 93 | 80.2356 | 0.260 | 2.104 | 0.039 | 0.414 | 0.206 | 0.368 | 0.204 | 0.122 | 0.061 |
| 22 | 229 | 80.2356 | 0.260 | 2.104 | 0.039 | 0.414 | 0.206 | 0.369 | 0.204 | 0.122 | 0.060 |
| 23 | 15 | 80.3692 | 0.256 | 1.944 | 0.045 | 0.413 | 0.234 | 0.407 | 0.333 | 0.121 | 0.069 |
| 24 | 71 | 80.3692 | 0.259 | 1.977 | 0.043 | 0.413 | 0.222 | 0.377 | 0.318 | 0.122 | 0.065 |
| 25 | 207 | 80.3692 | 0.259 | 1.978 | 0.043 | 0.413 | 0.222 | 0.377 | 0.317 | 0.122 | 0.065 |
| 26 | 33 | 80.5349 | 0.256 | 2.040 | 0.041 | 0.413 | 0.219 | 0.393 | 0.220 | 0.122 | 0.064 |
| 27 | 89 | 80.5349 | 0.261 | 2.077 | 0.040 | 0.413 | 0.208 | 0.370 | 0.208 | 0.122 | 0.061 |
| 28 | 225 | 80.5349 | 0.261 | 2.077 | 0.040 | 0.413 | 0.208 | 0.370 | 0.207 | 0.122 | 0.061 |
| 29 | 28 | 81.4969 | 0.260 | 2.024 | 0.042 | 0.413 | 0.219 | 0.394 | 0.224 | 0.121 | 0.064 |
| 30 | 84 | 81.4969 | 0.264 | 2.059 | 0.040 | 0.413 | 0.207 | 0.369 | 0.220 | 0.122 | 0.061 |
| 31 | 220 | 81.4969 | 0.264 | 2.060 | 0.040 | 0.413 | 0.207 | 0.369 | 0.219 | 0.122 | 0.061 |
| 32 | 1 | 82.2802 | 0.259 | 1.893 | 0.048 | 0.413 | 0.242 | 0.404 | 0.439 | 0.121 | 0.071 |
| 33 | 57 | 82.2802 | 0.260 | 1.926 | 0.045 | 0.413 | 0.229 | 0.374 | 0.414 | 0.121 | 0.067 |
| 34 | 193 | 82.2802 | 0.260 | 1.926 | 0.045 | 0.413 | 0.229 | 0.374 | 0.413 | 0.121 | 0.067 |
| 35 | 7 | 83.3181 | 0.262 | 1.920 | 0.046 | 0.413 | 0.234 | 0.401 | 0.396 | 0.121 | 0.069 |
| 36 | 63 | 83.3181 | 0.264 | 1.952 | 0.043 | 0.413 | 0.222 | 0.371 | 0.375 | 0.121 | 0.065 |
| 37 | 199 | 83.3181 | 0.263 | 1.952 | 0.043 | 0.413 | 0.222 | 0.371 | 0.374 | 0.121 | 0.065 |
| 38 | 19 | 83.4550 | 0.264 | 1.985 | 0.042 | 0.413 | 0.220 | 0.391 | 0.278 | 0.121 | 0.065 |
| 39 | 75 | 83.4550 | 0.267 | 2.016 | 0.040 | 0.413 | 0.209 | 0.363 | 0.267 | 0.121 | 0.062 |
| 40 | 211 | 83.4550 | 0.267 | 2.016 | 0.040 | 0.413 | 0.209 | 0.363 | 0.266 | 0.121 | 0.062 |
| 41 | 25 | 83.7192 | 0.266 | 2.013 | 0.041 | 0.413 | 0.215 | 0.388 | 0.245 | 0.121 | 0.063 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 42 | 81 | 83.7192 | 0.269 | 2.045 | 0.039 | 0.413 | 0.204 | 0.362 | 0.237 | 0.121 | 0.060 |
| 43 | 217 | 83.7192 | 0.269 | 2.046 | 0.039 | 0.413 | 0.204 | 0.362 | 0.236 | 0.121 | 0.060 |
| 44 | 34 | 87.3860 | 0.281 | 2.098 | 0.037 | 0.413 | 0.193 | 0.372 | 0.190 | 0.121 | 0.057 |
| 45 | 90 | 87.3860 | 0.286 | 2.127 | 0.036 | 0.413 | 0.184 | 0.349 | 0.179 | 0.121 | 0.054 |
| 46 | 226 | 87.3860 | 0.286 | 2.127 | 0.035 | 0.413 | 0.184 | 0.349 | 0.178 | 0.121 | 0.054 |
| 47 | 127 | 88.7159 | 0.297 | 2.206 | 0.033 | 0.413 | 0.170 | 0.328 | 0.162 | 0.121 | 0.050 |
| 48 | 261 | 88.7159 | 0.297 | 2.206 | 0.033 | 0.413 | 0.170 | 0.328 | 0.161 | 0.121 | 0.050 |
| 49 | 38 | 89.3983 | 0.294 | 2.153 | 0.035 | 0.412 | 0.179 | 0.366 | 0.179 | 0.121 | 0.053 |
| 50 | 94 | 89.3983 | 0.299 | 2.175 | 0.034 | 0.413 | 0.172 | 0.342 | 0.168 | 0.121 | 0.051 |
| 51 | 230 | 89.3983 | 0.299 | 2.175 | 0.034 | 0.413 | 0.172 | 0.343 | 0.167 | 0.121 | 0.051 |
| 52 | 11 | 91.6970 | 0.280 | 1.981 | 0.040 | 0.412 | 0.208 | 0.370 | 0.304 | 0.121 | 0.061 |
| 53 | 67 | 91.6970 | 0.281 | 2.001 | 0.037 | 0.413 | 0.199 | 0.340 | 0.287 | 0.121 | 0.059 |
| 54 | 203 | 91.6970 | 0.281 | 2.001 | 0.037 | 0.413 | 0.199 | 0.340 | 0.287 | 0.121 | 0.059 |
| 55 | 41 | 94.3473 | 0.309 | 2.201 | 0.031 | 0.412 | 0.163 | 0.326 | 0.152 | 0.121 | 0.048 |
| 56 | 97 | 94.3473 | 0.311 | 2.219 | 0.030 | 0.413 | 0.158 | 0.300 | 0.142 | 0.121 | 0.047 |
| 57 | 233 | 94.3473 | 0.311 | 2.219 | 0.030 | 0.413 | 0.158 | 0.301 | 0.141 | 0.121 | 0.047 |
| 58 | 262 | 101.0962 | 0.319 | 2.247 | 0.025 | 0.413 | 0.149 | 0.243 | 0.109 | 0.121 | 0.044 |
| 59 | 16 | 102.4478 | 0.301 | 2.018 | 0.032 | 0.412 | 0.184 | 0.316 | 0.218 | 0.121 | 0.054 |
| 60 | 72 | 102.4478 | 0.301 | 2.028 | 0.030 | 0.412 | 0.179 | 0.287 | 0.206 | 0.121 | 0.052 |
| 61 | 208 | 102.4478 | 0.301 | 2.028 | 0.030 | 0.412 | 0.178 | 0.288 | 0.205 | 0.121 | 0.052 |
| 62 | 263 | 103.7392 | 0.328 | 2.252 | 0.024 | 0.413 | 0.144 | 0.234 | 0.103 | 0.121 | 0.042 |
| 63 | 42 | 106.1299 | 0.336 | 2.218 | 0.026 | 0.412 | 0.143 | 0.277 | 0.118 | 0.121 | 0.042 |
| 64 | 98 | 106.1299 | 0.337 | 2.229 | 0.024 | 0.412 | 0.140 | 0.252 | 0.108 | 0.121 | 0.041 |
| 65 | 234 | 106.1299 | 0.337 | 2.229 | 0.024 | 0.412 | 0.140 | 0.252 | 0.108 | 0.121 | 0.041 |
| 66 | 264 | 106.4162 | 0.337 | 2.256 | 0.023 | 0.412 | 0.139 | 0.226 | 0.097 | 0.121 | 0.041 |
| 67 | 20 | 109.0025 | 0.318 | 2.062 | 0.028 | 0.411 | 0.166 | 0.295 | 0.173 | 0.121 | 0.049 |
| 68 | 76 | 109.0025 | 0.318 | 2.069 | 0.027 | 0.412 | 0.162 | 0.267 | 0.163 | 0.121 | 0.048 |
| 69 | 212 | 109.0025 | 0.318 | 2.069 | 0.027 | 0.412 | 0.162 | 0.268 | 0.162 | 0.121 | 0.048 |
| 70 | 46 | 109.1273 | 0.342 | 2.249 | 0.024 | 0.412 | 0.137 | 0.239 | 0.101 | 0.121 | 0.040 |
| 71 | 102 | 109.1273 | 0.347 | 2.258 | 0.022 | 0.412 | 0.134 | 0.217 | 0.091 | 0.121 | 0.039 |
| 72 | 238 | 109.1273 | 0.347 | 2.258 | 0.022 | 0.412 | 0.134 | 0.218 | 0.091 | 0.121 | 0.039 |
| 73 | 29 | 110.1905 | 0.335 | 2.130 | 0.027 | 0.411 | 0.150 | 0.294 | 0.133 | 0.121 | 0.044 |
| 74 | 85 | 110.1905 | 0.335 | 2.138 | 0.025 | 0.412 | 0.147 | 0.268 | 0.126 | 0.121 | 0.043 |
| 75 | 221 | 110.1905 | 0.335 | 2.138 | 0.025 | 0.412 | 0.147 | 0.269 | 0.126 | 0.121 | 0.043 |
| 76 | 8 | 110.9265 | 0.303 | 1.970 | 0.030 | 0.411 | 0.188 | 0.289 | 0.237 | 0.121 | 0.055 |
| 77 | 64 | 110.9265 | 0.302 | 1.974 | 0.028 | 0.412 | 0.184 | 0.260 | 0.221 | 0.121 | 0.054 |
| 78 | 200 | 110.9265 | 0.302 | 1.974 | 0.028 | 0.412 | 0.184 | 0.260 | 0.221 | 0.121 | 0.054 |
| 79 | 47 | 111.8726 | 0.353 | 2.250 | 0.022 | 0.412 | 0.132 | 0.231 | 0.095 | 0.121 | 0.039 |
| 80 | 103 | 111.8726 | 0.358 | 2.257 | 0.021 | 0.412 | 0.129 | 0.209 | 0.085 | 0.121 | 0.038 |
| 81 | 239 | 111.8726 | 0.358 | 2.257 | 0.021 | 0.412 | 0.129 | 0.209 | 0.085 | 0.121 | 0.038 |
| 82 | 48 | 114.6519 | 0.364 | 2.251 | 0.021 | 0.412 | 0.126 | 0.223 | 0.089 | 0.121 | 0.037 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 83 | 104 | 114.6519 | 0.369 | 2.255 | 0.020 | 0.412 | 0.124 | 0.201 | 0.080 | 0.121 | 0.036 |
| 84 | 240 | 114.6519 | 0.369 | 2.255 | 0.020 | 0.412 | 0.124 | 0.201 | 0.080 | 0.121 | 0.036 |
| 85 | 49 | 117.4653 | 0.375 | 2.250 | 0.020 | 0.411 | 0.121 | 0.214 | 0.083 | 0.121 | 0.036 |
| 86 | 105 | 117.4653 | 0.380 | 2.253 | 0.019 | 0.411 | 0.119 | 0.193 | 0.075 | 0.121 | 0.035 |
| 87 | 241 | 117.4653 | 0.380 | 2.253 | 0.019 | 0.411 | 0.119 | 0.194 | 0.075 | 0.121 | 0.035 |
| 88 | 50 | 120.3129 | 0.387 | 2.249 | 0.019 | 0.411 | 0.116 | 0.206 | 0.078 | 0.121 | 0.034 |
| 89 | 106 | 120.3129 | 0.392 | 2.252 | 0.018 | 0.411 | 0.115 | 0.185 | 0.070 | 0.121 | 0.034 |
| 90 | 242 | 120.3129 | 0.392 | 2.252 | 0.018 | 0.411 | 0.115 | 0.186 | 0.070 | 0.121 | 0.034 |
| 91 | 43 | 121.8328 | 0.383 | 2.235 | 0.021 | 0.411 | 0.118 | 0.226 | 0.085 | 0.121 | 0.035 |
| 92 | 99 | 121.8328 | 0.384 | 2.237 | 0.019 | 0.411 | 0.117 | 0.202 | 0.077 | 0.121 | 0.035 |
| 93 | 235 | 121.8328 | 0.384 | 2.237 | 0.019 | 0.411 | 0.117 | 0.203 | 0.077 | 0.121 | 0.035 |
| 94 | 51 | 123.1945 | 0.399 | 2.248 | 0.018 | 0.411 | 0.112 | 0.199 | 0.073 | 0.121 | 0.033 |
| 95 | 107 | 123.1945 | 0.398 | 2.249 | 0.017 | 0.411 | 0.112 | 0.176 | 0.065 | 0.121 | 0.033 |
| 96 | 243 | 123.1945 | 0.398 | 2.249 | 0.017 | 0.411 | 0.112 | 0.177 | 0.065 | 0.121 | 0.033 |
| 97 | 52 | 126.1103 | 0.407 | 2.246 | 0.017 | 0.411 | 0.108 | 0.190 | 0.068 | 0.121 | 0.032 |
| 98 | 108 | 126.1103 | 0.404 | 2.246 | 0.016 | 0.411 | 0.110 | 0.167 | 0.061 | 0.121 | 0.032 |
| 99 | 244 | 126.1103 | 0.404 | 2.245 | 0.016 | 0.411 | 0.110 | 0.167 | 0.061 | 0.121 | 0.032 |
| 100 | 53 | 129.0601 | 0.412 | 2.242 | 0.016 | 0.410 | 0.106 | 0.180 | 0.063 | 0.121 | 0.031 |
| 101 | 109 | 129.0601 | 0.409 | 2.242 | 0.015 | 0.411 | 0.108 | 0.157 | 0.056 | 0.121 | 0.032 |
| 102 | 245 | 129.0601 | 0.409 | 2.242 | 0.015 | 0.411 | 0.108 | 0.157 | 0.056 | 0.121 | 0.032 |
| 103 | 2 | 129.4213 | 0.326 | 1.977 | 0.024 | 0.410 | 0.179 | 0.234 | 0.192 | 0.121 | 0.053 |
| 104 | 58 | 129.4213 | 0.327 | 1.986 | 0.023 | 0.411 | 0.176 | 0.210 | 0.181 | 0.121 | 0.052 |
| 105 | 194 | 129.4213 | 0.327 | 1.986 | 0.023 | 0.411 | 0.176 | 0.211 | 0.180 | 0.121 | 0.052 |
| 106 | 17 | 129.8252 | 0.351 | 2.069 | 0.022 | 0.410 | 0.143 | 0.237 | 0.139 | 0.121 | 0.042 |
| 107 | 73 | 129.8252 | 0.352 | 2.077 | 0.021 | 0.411 | 0.139 | 0.213 | 0.130 | 0.121 | 0.041 |
| 108 | 209 | 129.8252 | 0.352 | 2.077 | 0.021 | 0.411 | 0.139 | 0.213 | 0.130 | 0.121 | 0.041 |
| 109 | 30 | 129.9582 | 0.381 | 2.160 | 0.021 | 0.410 | 0.121 | 0.243 | 0.095 | 0.121 | 0.036 |
| 110 | 86 | 129.9582 | 0.382 | 2.166 | 0.020 | 0.410 | 0.119 | 0.218 | 0.089 | 0.121 | 0.035 |
| 111 | 222 | 129.9582 | 0.382 | 2.166 | 0.020 | 0.410 | 0.119 | 0.219 | 0.089 | 0.121 | 0.035 |
| 112 | 26 | 130.0074 | 0.370 | 2.131 | 0.021 | 0.410 | 0.128 | 0.241 | 0.108 | 0.121 | 0.038 |
| 113 | 82 | 130.0074 | 0.371 | 2.137 | 0.020 | 0.410 | 0.125 | 0.216 | 0.102 | 0.121 | 0.037 |
| 114 | 218 | 130.0074 | 0.371 | 2.137 | 0.020 | 0.410 | 0.125 | 0.217 | 0.101 | 0.121 | 0.037 |
| 115 | 35 | 130.0653 | 0.391 | 2.187 | 0.020 | 0.410 | 0.115 | 0.241 | 0.086 | 0.120 | 0.034 |
| 116 | 91 | 130.0653 | 0.393 | 2.192 | 0.019 | 0.410 | 0.114 | 0.216 | 0.078 | 0.121 | 0.033 |
| 117 | 227 | 130.0653 | 0.393 | 2.192 | 0.019 | 0.410 | 0.114 | 0.217 | 0.078 | 0.121 | 0.034 |
| 118 | 21 | 130.1006 | 0.361 | 2.101 | 0.022 | 0.410 | 0.135 | 0.238 | 0.122 | 0.121 | 0.040 |
| 119 | 77 | 130.1006 | 0.362 | 2.107 | 0.020 | 0.410 | 0.132 | 0.214 | 0.115 | 0.121 | 0.039 |
| 120 | 213 | 130.1006 | 0.362 | 2.108 | 0.020 | 0.410 | 0.132 | 0.215 | 0.115 | 0.121 | 0.039 |
| 121 | 44 | 131.7744 | 0.413 | 2.237 | 0.018 | 0.410 | 0.106 | 0.198 | 0.070 | 0.121 | 0.031 |
| 122 | 100 | 131.7744 | 0.407 | 2.234 | 0.017 | 0.411 | 0.109 | 0.176 | 0.062 | 0.121 | 0.032 |
| 123 | 236 | 131.7744 | 0.407 | 2.234 | 0.016 | 0.411 | 0.109 | 0.177 | 0.062 | 0.121 | 0.032 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 124 | 54 | 132.0441 | 0.417 | 2.239 | 0.015 | 0.410 | 0.105 | 0.170 | 0.059 | 0.121 | 0.031 |
| 125 | 110 | 132.0441 | 0.415 | 2.239 | 0.014 | 0.411 | 0.106 | 0.146 | 0.051 | 0.121 | 0.031 |
| 126 | 246 | 132.0441 | 0.415 | 2.239 | 0.014 | 0.411 | 0.106 | 0.147 | 0.051 | 0.121 | 0.031 |
| 127 | 39 | 134.8266 | 0.411 | 2.215 | 0.018 | 0.410 | 0.106 | 0.208 | 0.072 | 0.120 | 0.031 |
| 128 | 95 | 134.8266 | 0.409 | 2.215 | 0.017 | 0.410 | 0.107 | 0.186 | 0.065 | 0.121 | 0.032 |
| 129 | 231 | 134.8266 | 0.409 | 2.215 | 0.017 | 0.410 | 0.107 | 0.187 | 0.065 | 0.121 | 0.032 |
| 130 | 55 | 135.0621 | 0.422 | 2.235 | 0.015 | 0.410 | 0.103 | 0.159 | 0.054 | 0.121 | 0.030 |
| 131 | 111 | 135.0621 | 0.420 | 2.236 | 0.014 | 0.410 | 0.105 | 0.135 | 0.047 | 0.121 | 0.031 |
| 132 | 247 | 135.0621 | 0.420 | 2.236 | 0.014 | 0.410 | 0.105 | 0.136 | 0.047 | 0.121 | 0.031 |
| 133 | 56 | 138.1142 | 0.426 | 2.232 | 0.014 | 0.410 | 0.102 | 0.147 | 0.049 | 0.121 | 0.030 |
| 134 | 112 | 138.1142 | 0.424 | 2.233 | 0.013 | 0.410 | 0.103 | 0.124 | 0.042 | 0.121 | 0.030 |
| 135 | 248 | 138.1142 | 0.424 | 2.233 | 0.013 | 0.410 | 0.103 | 0.124 | 0.042 | 0.121 | 0.030 |
| 136 | 45 | 167.7286 | 0.458 | 2.199 | 0.017 | 0.409 | 0.090 | 0.051 | 0.017 | 0.120 | 0.027 |
| 137 | 101 | 167.7286 | 0.456 | 2.204 | 0.016 | 0.409 | 0.092 | 0.039 | 0.014 | 0.120 | 0.027 |
| 138 | 237 | 167.7286 | 0.456 | 2.204 | 0.016 | 0.409 | 0.092 | 0.040 | 0.014 | 0.120 | 0.027 |
| 139 | 22 | 170.3164 | 0.433 | 2.136 | 0.023 | 0.407 | 0.101 | 0.091 | 0.060 | 0.120 | 0.030 |
| 140 | 78 | 170.3164 | 0.433 | 2.141 | 0.022 | 0.408 | 0.099 | 0.077 | 0.053 | 0.120 | 0.029 |
| 141 | 214 | 170.3164 | 0.433 | 2.141 | 0.022 | 0.408 | 0.099 | 0.078 | 0.052 | 0.120 | 0.029 |
| 142 | 40 | 208.2658 | 0.484 | 2.192 | 0.013 | 0.407 | 0.082 | 0.025 | 0.011 | 0.120 | 0.024 |
| 143 | 96 | 208.2658 | 0.483 | 2.196 | 0.012 | 0.407 | 0.084 | 0.016 | 0.008 | 0.120 | 0.025 |
| 144 | 232 | 208.2658 | 0.482 | 2.196 | 0.012 | 0.407 | 0.084 | 0.017 | 0.008 | 0.120 | 0.025 |
| 145 | 31 | 215.9733 | 0.494 | 2.194 | 0.016 | 0.405 | 0.076 | 0.048 | 0.023 | 0.119 | 0.022 |
| 146 | 87 | 215.9733 | 0.490 | 2.192 | 0.014 | 0.406 | 0.079 | 0.036 | 0.019 | 0.119 | 0.023 |
| 147 | 223 | 215.9733 | 0.490 | 2.192 | 0.014 | 0.406 | 0.079 | 0.037 | 0.019 | 0.119 | 0.023 |
| 148 | 126 | 222.8766 | 0.490 | 2.197 | 0.011 | 0.407 | 0.082 | 0.007 | 0.004 | 0.120 | 0.024 |
| 149 | 260 | 222.8766 | 0.490 | 2.197 | 0.011 | 0.407 | 0.082 | 0.007 | 0.004 | 0.120 | 0.024 |
| 150 | 3 | 228.5562 | 0.452 | 2.108 | 0.019 | 0.404 | 0.112 | 0.041 | 0.050 | 0.119 | 0.033 |
| 151 | 59 | 228.5562 | 0.449 | 2.106 | 0.018 | 0.405 | 0.112 | 0.030 | 0.044 | 0.119 | 0.033 |
| 152 | 195 | 228.5562 | 0.449 | 2.106 | 0.018 | 0.405 | 0.112 | 0.031 | 0.044 | 0.119 | 0.033 |
| 153 | 12 | 254.7139 | 0.485 | 2.152 | 0.016 | 0.402 | 0.090 | 0.029 | 0.031 | 0.118 | 0.026 |
| 154 | 68 | 254.7139 | 0.483 | 2.151 | 0.015 | 0.403 | 0.090 | 0.019 | 0.026 | 0.119 | 0.026 |
| 155 | 204 | 254.7139 | 0.483 | 2.151 | 0.015 | 0.403 | 0.090 | 0.020 | 0.025 | 0.119 | 0.026 |
| 156 | 36 | 264.5698 | 0.505 | 2.187 | 0.010 | 0.405 | 0.074 | 0.007 | 0.004 | 0.119 | 0.022 |
| 157 | 92 | 264.5698 | 0.505 | 2.193 | 0.010 | 0.405 | 0.076 | 0.006 | 0.001 | 0.119 | 0.022 |
| 158 | 228 | 264.5698 | 0.505 | 2.193 | 0.010 | 0.405 | 0.076 | 0.006 | 0.001 | 0.119 | 0.022 |
| 159 | 32 | 333.6127 | 0.519 | 2.186 | 0.009 | 0.402 | 0.068 | 0.009 | 0.000 | 0.118 | 0.020 |
| 160 | 88 | 333.6127 | 0.520 | 2.193 | 0.008 | 0.403 | 0.070 | 0.011 | 0.000 | 0.118 | 0.021 |
| 161 | 224 | 333.6127 | 0.520 | 2.193 | 0.008 | 0.403 | 0.070 | 0.010 | 0.000 | 0.118 | 0.021 |
| 162 | 23 | 333.8201 | 0.521 | 2.188 | 0.011 | 0.400 | 0.070 | 0.008 | 0.008 | 0.118 | 0.021 |
| 163 | 79 | 333.8201 | 0.519 | 2.187 | 0.010 | 0.401 | 0.070 | 0.008 | 0.004 | 0.118 | 0.021 |
| 164 | 215 | 333.8201 | 0.519 | 2.187 | 0.010 | 0.401 | 0.070 | 0.008 | 0.004 | 0.118 | 0.021 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 165 | 123 | 357.0172 | 0.524 | 2.194 | 0.008 | 0.402 | 0.069 | 0.015 | 0.000 | 0.118 | 0.020 |
| 166 | 257 | 357.0172 | 0.524 | 2.194 | 0.008 | 0.402 | 0.069 | 0.014 | 0.000 | 0.118 | 0.020 |
| 167 | 27 | 416.6143 | 0.527 | 2.185 | 0.008 | 0.399 | 0.068 | 0.021 | 0.000 | 0.117 | 0.020 |
| 168 | 83 | 416.6143 | 0.529 | 2.192 | 0.007 | 0.400 | 0.066 | 0.024 | 0.000 | 0.118 | 0.019 |
| 169 | 219 | 416.6143 | 0.529 | 2.192 | 0.007 | 0.400 | 0.066 | 0.022 | 0.000 | 0.118 | 0.019 |
| 170 | 13 | 499.2391 | 0.531 | 2.186 | 0.009 | 0.396 | 0.070 | 0.028 | 0.000 | 0.116 | 0.021 |
| 171 | 69 | 499.2391 | 0.531 | 2.186 | 0.009 | 0.396 | 0.070 | 0.032 | 0.000 | 0.117 | 0.020 |
| 172 | 205 | 499.2391 | 0.531 | 2.186 | 0.009 | 0.396 | 0.070 | 0.031 | 0.000 | 0.117 | 0.020 |
| 173 | 24 | 503.8640 | 0.531 | 2.185 | 0.007 | 0.397 | 0.068 | 0.034 | 0.000 | 0.117 | 0.020 |
| 174 | 80 | 503.8640 | 0.533 | 2.191 | 0.007 | 0.398 | 0.066 | 0.038 | 0.000 | 0.117 | 0.019 |
| 175 | 216 | 503.8640 | 0.533 | 2.191 | 0.007 | 0.398 | 0.066 | 0.036 | 0.000 | 0.117 | 0.019 |
| 176 | 4 | 514.2514 | 0.527 | 2.179 | 0.010 | 0.394 | 0.074 | 0.025 | 0.003 | 0.116 | 0.022 |
| 177 | 60 | 514.2514 | 0.527 | 2.178 | 0.010 | 0.395 | 0.074 | 0.029 | 0.000 | 0.116 | 0.022 |
| 178 | 196 | 514.2514 | 0.527 | 2.178 | 0.010 | 0.395 | 0.074 | 0.027 | 0.000 | 0.116 | 0.022 |
| 179 | 120 | 551.8250 | 0.535 | 2.193 | 0.006 | 0.397 | 0.065 | 0.046 | 0.000 | 0.117 | 0.019 |
| 180 | 254 | 551.8250 | 0.535 | 2.193 | 0.006 | 0.397 | 0.065 | 0.044 | 0.000 | 0.117 | 0.019 |
| 181 | 18 | 618.5337 | 0.534 | 2.185 | 0.007 | 0.395 | 0.068 | 0.052 | 0.000 | 0.116 | 0.020 |
| 182 | 74 | 618.5337 | 0.536 | 2.191 | 0.007 | 0.396 | 0.066 | 0.056 | 0.000 | 0.116 | 0.020 |
| 183 | 210 | 618.5337 | 0.536 | 2.191 | 0.007 | 0.396 | 0.066 | 0.055 | 0.000 | 0.116 | 0.020 |
| 184 | 5 | 699.9532 | 0.533 | 2.182 | 0.008 | 0.391 | 0.071 | 0.057 | 0.000 | 0.115 | 0.021 |
| 185 | 61 | 699.9532 | 0.533 | 2.182 | 0.008 | 0.392 | 0.071 | 0.063 | 0.000 | 0.115 | 0.021 |
| 186 | 197 | 699.9532 | 0.533 | 2.182 | 0.008 | 0.392 | 0.071 | 0.061 | 0.000 | 0.115 | 0.021 |
| 187 | 14 | 771.1717 | 0.536 | 2.183 | 0.006 | 0.392 | 0.069 | 0.071 | 0.000 | 0.115 | 0.020 |
| 188 | 70 | 771.1717 | 0.537 | 2.189 | 0.006 | 0.393 | 0.067 | 0.076 | 0.000 | 0.116 | 0.020 |
| 189 | 206 | 771.1717 | 0.537 | 2.189 | 0.006 | 0.393 | 0.067 | 0.074 | 0.000 | 0.116 | 0.020 |
| 190 | 117 | 825.2729 | 0.537 | 2.189 | 0.006 | 0.393 | 0.067 | 0.083 | 0.000 | 0.115 | 0.020 |
| 191 | 252 | 825.2729 | 0.537 | 2.189 | 0.006 | 0.393 | 0.067 | 0.081 | 0.000 | 0.115 | 0.020 |
| 192 | 9 | 954.4603 | 0.531 | 2.172 | 0.006 | 0.390 | 0.074 | 0.088 | 0.000 | 0.115 | 0.022 |
| 193 | 65 | 954.4603 | 0.532 | 2.180 | 0.006 | 0.391 | 0.071 | 0.093 | 0.000 | 0.115 | 0.021 |
| 194 | 201 | 954.4603 | 0.532 | 2.180 | 0.006 | 0.391 | 0.071 | 0.091 | 0.000 | 0.115 | 0.021 |
| 195 | 6 | 1106.2120 | 0.526 | 2.163 | 0.006 | 0.389 | 0.077 | 0.098 | 0.000 | 0.114 | 0.023 |
| 196 | 62 | 1106.2120 | 0.527 | 2.171 | 0.006 | 0.390 | 0.074 | 0.103 | 0.000 | 0.115 | 0.022 |
| 197 | 198 | 1106.2120 | 0.527 | 2.171 | 0.006 | 0.390 | 0.074 | 0.101 | 0.000 | 0.115 | 0.022 |
| 198 | 114 | 1157.0650 | 0.525 | 2.168 | 0.005 | 0.390 | 0.075 | 0.105 | 0.000 | 0.115 | 0.022 |
| 199 | 249 | 1157.0650 | 0.525 | 2.168 | 0.005 | 0.390 | 0.075 | 0.103 | 0.000 | 0.115 | 0.022 |

D.2 Lateral Unit P_{cmd} Step Input Time Response (45% Triple Failure)

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 1 | 119 | 65.4696 | 0.145 | 1.339 | 0.062 | 0.416 | 0.442 | 0.408 | 0.765 | 0.122 | 0.130 |
| 2 | 253 | 65.4696 | 0.145 | 1.339 | 0.061 | 0.416 | 0.442 | 0.407 | 0.763 | 0.122 | 0.130 |
| 3 | 118 | 65.5666 | 0.145 | 1.319 | 0.063 | 0.416 | 0.452 | 0.408 | 0.836 | 0.122 | 0.133 |
| 4 | 122 | 67.0399 | 0.147 | 1.397 | 0.058 | 0.416 | 0.417 | 0.393 | 0.590 | 0.122 | 0.122 |
| 5 | 256 | 67.0399 | 0.147 | 1.398 | 0.058 | 0.416 | 0.416 | 0.392 | 0.589 | 0.122 | 0.122 |
| 6 | 121 | 67.4267 | 0.148 | 1.385 | 0.059 | 0.416 | 0.421 | 0.393 | 0.648 | 0.122 | 0.124 |
| 7 | 255 | 67.4267 | 0.148 | 1.386 | 0.058 | 0.416 | 0.421 | 0.392 | 0.646 | 0.122 | 0.124 |
| 8 | 124 | 67.6717 | 0.147 | 1.420 | 0.056 | 0.416 | 0.407 | 0.385 | 0.529 | 0.122 | 0.120 |
| 9 | 116 | 68.8746 | 0.151 | 1.351 | 0.061 | 0.416 | 0.438 | 0.392 | 0.823 | 0.122 | 0.129 |
| 10 | 251 | 68.8746 | 0.151 | 1.352 | 0.061 | 0.416 | 0.438 | 0.391 | 0.821 | 0.122 | 0.129 |
| 11 | 115 | 70.9929 | 0.154 | 1.359 | 0.060 | 0.416 | 0.435 | 0.382 | 0.844 | 0.122 | 0.128 |
| 12 | 10 | 74.2746 | 0.160 | 1.343 | 0.060 | 0.415 | 0.439 | 0.389 | 0.788 | 0.122 | 0.129 |
| 13 | 66 | 74.2746 | 0.161 | 1.426 | 0.056 | 0.415 | 0.404 | 0.365 | 0.708 | 0.122 | 0.119 |
| 14 | 202 | 74.2746 | 0.160 | 1.426 | 0.056 | 0.415 | 0.404 | 0.364 | 0.705 | 0.122 | 0.119 |
| 15 | 113 | 75.5664 | 0.162 | 1.400 | 0.058 | 0.415 | 0.417 | 0.359 | 0.802 | 0.122 | 0.123 |
| 16 | 250 | 77.0323 | 0.165 | 1.436 | 0.055 | 0.415 | 0.400 | 0.352 | 0.720 | 0.122 | 0.117 |
| 17 | 258 | 77.2143 | 0.163 | 1.530 | 0.047 | 0.416 | 0.362 | 0.327 | 0.375 | 0.122 | 0.106 |
| 18 | 125 | 77.2914 | 0.163 | 1.549 | 0.046 | 0.416 | 0.356 | 0.323 | 0.341 | 0.122 | 0.105 |
| 19 | 259 | 77.2914 | 0.163 | 1.550 | 0.045 | 0.416 | 0.356 | 0.322 | 0.340 | 0.122 | 0.105 |
| 20 | 37 | 80.2356 | 0.169 | 1.545 | 0.045 | 0.415 | 0.356 | 0.330 | 0.349 | 0.122 | 0.105 |
| 21 | 93 | 80.2356 | 0.172 | 1.610 | 0.044 | 0.415 | 0.335 | 0.313 | 0.304 | 0.122 | 0.098 |
| 22 | 229 | 80.2356 | 0.172 | 1.610 | 0.044 | 0.415 | 0.335 | 0.313 | 0.303 | 0.122 | 0.098 |
| 23 | 15 | 80.3692 | 0.169 | 1.426 | 0.051 | 0.415 | 0.399 | 0.348 | 0.599 | 0.122 | 0.117 |
| 24 | 71 | 80.3692 | 0.170 | 1.490 | 0.048 | 0.415 | 0.373 | 0.323 | 0.543 | 0.122 | 0.110 |
| 25 | 207 | 80.3692 | 0.170 | 1.490 | 0.048 | 0.415 | 0.373 | 0.323 | 0.541 | 0.122 | 0.110 |
| 26 | 33 | 80.5349 | 0.170 | 1.521 | 0.046 | 0.415 | 0.363 | 0.334 | 0.377 | 0.122 | 0.107 |
| 27 | 89 | 80.5349 | 0.172 | 1.586 | 0.045 | 0.415 | 0.341 | 0.315 | 0.340 | 0.122 | 0.100 |
| 28 | 225 | 80.5349 | 0.172 | 1.586 | 0.044 | 0.415 | 0.341 | 0.315 | 0.339 | 0.122 | 0.100 |
| 29 | 28 | 81.4969 | 0.172 | 1.513 | 0.047 | 0.415 | 0.365 | 0.334 | 0.412 | 0.122 | 0.107 |
| 30 | 84 | 81.4969 | 0.174 | 1.576 | 0.045 | 0.415 | 0.342 | 0.314 | 0.377 | 0.122 | 0.101 |
| 31 | 220 | 81.4969 | 0.174 | 1.576 | 0.045 | 0.415 | 0.342 | 0.314 | 0.376 | 0.122 | 0.101 |
| 32 | 1 | 82.2802 | 0.171 | 1.390 | 0.055 | 0.415 | 0.420 | 0.350 | 0.755 | 0.122 | 0.124 |
| 33 | 57 | 82.2802 | 0.171 | 1.453 | 0.052 | 0.415 | 0.391 | 0.325 | 0.686 | 0.122 | 0.115 |
| 34 | 193 | 82.2802 | 0.171 | 1.454 | 0.051 | 0.415 | 0.391 | 0.325 | 0.684 | 0.122 | 0.115 |
| 35 | 7 | 83.3181 | 0.173 | 1.421 | 0.053 | 0.415 | 0.404 | 0.346 | 0.686 | 0.122 | 0.119 |
| 36 | 63 | 83.3181 | 0.173 | 1.484 | 0.050 | 0.415 | 0.377 | 0.321 | 0.625 | 0.122 | 0.111 |
| 37 | 199 | 83.3181 | 0.173 | 1.484 | 0.050 | 0.415 | 0.377 | 0.321 | 0.623 | 0.122 | 0.111 |
| 38 | 19 | 83.4550 | 0.175 | 1.486 | 0.048 | 0.415 | 0.373 | 0.332 | 0.496 | 0.122 | 0.110 |
| 39 | 75 | 83.4550 | 0.176 | 1.546 | 0.045 | 0.415 | 0.350 | 0.309 | 0.453 | 0.122 | 0.103 |
| 40 | 211 | 83.4550 | 0.176 | 1.546 | 0.045 | 0.415 | 0.350 | 0.308 | 0.452 | 0.122 | 0.103 |
| 41 | 25 | 83.7191 | 0.177 | 1.516 | 0.046 | 0.415 | 0.362 | 0.328 | 0.438 | 0.122 | 0.106 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ | |
|----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|-------|
| 42 | 81 | 83.7191 | 0.178 | 1.578 | 0.044 | 0.415 | 0.340 | 0.307 | 0.402 | 0.122 | 0.100 |
| 43 | 217 | 83.7191 | 0.178 | 1.578 | 0.044 | 0.415 | 0.339 | 0.307 | 0.401 | 0.122 | 0.100 |
| 44 | 34 | 87.3860 | 0.189 | 1.636 | 0.042 | 0.415 | 0.321 | 0.312 | 0.304 | 0.122 | 0.094 |
| 45 | 90 | 87.3860 | 0.191 | 1.693 | 0.040 | 0.415 | 0.302 | 0.292 | 0.285 | 0.122 | 0.089 |
| 46 | 226 | 87.3860 | 0.191 | 1.694 | 0.040 | 0.415 | 0.302 | 0.292 | 0.284 | 0.122 | 0.089 |
| 47 | 127 | 88.7159 | 0.198 | 1.800 | 0.038 | 0.415 | 0.275 | 0.275 | 0.221 | 0.122 | 0.081 |
| 48 | 261 | 88.7159 | 0.198 | 1.801 | 0.037 | 0.415 | 0.275 | 0.275 | 0.220 | 0.122 | 0.081 |
| 49 | 38 | 89.3983 | 0.199 | 1.717 | 0.040 | 0.415 | 0.296 | 0.305 | 0.250 | 0.122 | 0.087 |
| 50 | 94 | 89.3983 | 0.200 | 1.767 | 0.038 | 0.415 | 0.281 | 0.285 | 0.230 | 0.122 | 0.083 |
| 51 | 230 | 89.3983 | 0.200 | 1.768 | 0.038 | 0.415 | 0.281 | 0.285 | 0.230 | 0.122 | 0.083 |
| 52 | 11 | 91.6970 | 0.187 | 1.528 | 0.046 | 0.415 | 0.356 | 0.312 | 0.519 | 0.122 | 0.105 |
| 53 | 67 | 91.6970 | 0.187 | 1.575 | 0.043 | 0.415 | 0.336 | 0.287 | 0.476 | 0.122 | 0.099 |
| 54 | 203 | 91.6970 | 0.187 | 1.575 | 0.043 | 0.415 | 0.336 | 0.286 | 0.474 | 0.122 | 0.099 |
| 55 | 41 | 94.3473 | 0.208 | 1.810 | 0.036 | 0.415 | 0.268 | 0.272 | 0.213 | 0.122 | 0.079 |
| 56 | 97 | 94.3473 | 0.207 | 1.857 | 0.034 | 0.415 | 0.256 | 0.250 | 0.193 | 0.122 | 0.075 |
| 57 | 233 | 94.3473 | 0.207 | 1.857 | 0.034 | 0.415 | 0.256 | 0.250 | 0.192 | 0.122 | 0.075 |
| 58 | 262 | 101.0962 | 0.211 | 1.931 | 0.029 | 0.415 | 0.237 | 0.202 | 0.149 | 0.122 | 0.070 |
| 59 | 16 | 102.4478 | 0.204 | 1.620 | 0.037 | 0.414 | 0.313 | 0.259 | 0.367 | 0.122 | 0.092 |
| 60 | 72 | 102.4478 | 0.202 | 1.649 | 0.034 | 0.415 | 0.301 | 0.236 | 0.340 | 0.122 | 0.089 |
| 61 | 208 | 102.4478 | 0.202 | 1.650 | 0.034 | 0.415 | 0.301 | 0.236 | 0.339 | 0.122 | 0.089 |
| 62 | 263 | 103.7392 | 0.217 | 1.957 | 0.027 | 0.415 | 0.228 | 0.194 | 0.140 | 0.122 | 0.067 |
| 63 | 42 | 106.1299 | 0.227 | 1.906 | 0.030 | 0.415 | 0.235 | 0.228 | 0.165 | 0.122 | 0.069 |
| 64 | 98 | 106.1299 | 0.226 | 1.942 | 0.028 | 0.415 | 0.226 | 0.206 | 0.146 | 0.122 | 0.066 |
| 65 | 234 | 106.1299 | 0.226 | 1.943 | 0.028 | 0.415 | 0.226 | 0.206 | 0.145 | 0.122 | 0.066 |
| 66 | 264 | 106.4162 | 0.224 | 1.985 | 0.026 | 0.415 | 0.220 | 0.186 | 0.132 | 0.122 | 0.065 |
| 67 | 20 | 109.0025 | 0.216 | 1.701 | 0.033 | 0.414 | 0.282 | 0.239 | 0.290 | 0.122 | 0.083 |
| 68 | 76 | 109.0025 | 0.214 | 1.726 | 0.031 | 0.414 | 0.273 | 0.217 | 0.270 | 0.122 | 0.080 |
| 69 | 212 | 109.0025 | 0.214 | 1.726 | 0.030 | 0.414 | 0.273 | 0.217 | 0.269 | 0.122 | 0.080 |
| 70 | 46 | 109.1273 | 0.229 | 1.972 | 0.027 | 0.415 | 0.220 | 0.199 | 0.142 | 0.122 | 0.065 |
| 71 | 102 | 109.1273 | 0.231 | 2.010 | 0.025 | 0.415 | 0.211 | 0.179 | 0.124 | 0.122 | 0.062 |
| 72 | 238 | 109.1273 | 0.231 | 2.010 | 0.025 | 0.415 | 0.211 | 0.179 | 0.124 | 0.122 | 0.062 |
| 73 | 29 | 110.1905 | 0.229 | 1.802 | 0.031 | 0.414 | 0.253 | 0.238 | 0.223 | 0.122 | 0.074 |
| 74 | 85 | 110.1905 | 0.227 | 1.829 | 0.029 | 0.414 | 0.244 | 0.216 | 0.210 | 0.122 | 0.072 |
| 75 | 221 | 110.1905 | 0.227 | 1.829 | 0.029 | 0.414 | 0.244 | 0.216 | 0.209 | 0.122 | 0.072 |
| 76 | 8 | 110.9265 | 0.206 | 1.589 | 0.035 | 0.414 | 0.324 | 0.234 | 0.393 | 0.122 | 0.095 |
| 77 | 64 | 110.9265 | 0.203 | 1.608 | 0.032 | 0.414 | 0.314 | 0.211 | 0.362 | 0.122 | 0.092 |
| 78 | 200 | 110.9265 | 0.203 | 1.609 | 0.032 | 0.414 | 0.314 | 0.211 | 0.361 | 0.122 | 0.092 |
| 79 | 47 | 111.8726 | 0.237 | 1.997 | 0.026 | 0.415 | 0.211 | 0.190 | 0.132 | 0.122 | 0.062 |
| 80 | 103 | 111.8726 | 0.239 | 2.030 | 0.024 | 0.415 | 0.204 | 0.171 | 0.116 | 0.122 | 0.060 |
| 81 | 239 | 111.8726 | 0.239 | 2.030 | 0.024 | 0.415 | 0.204 | 0.171 | 0.116 | 0.122 | 0.060 |
| 82 | 48 | 114.6519 | 0.245 | 2.021 | 0.025 | 0.414 | 0.202 | 0.182 | 0.123 | 0.122 | 0.059 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 83 | 104 | 114.6519 | 0.247 | 2.049 | 0.023 | 0.414 | 0.196 | 0.164 | 0.108 | 0.122 | 0.058 |
| 84 | 240 | 114.6519 | 0.247 | 2.049 | 0.023 | 0.414 | 0.196 | 0.164 | 0.108 | 0.122 | 0.058 |
| 85 | 49 | 117.4653 | 0.254 | 2.042 | 0.024 | 0.414 | 0.194 | 0.174 | 0.114 | 0.122 | 0.057 |
| 86 | 105 | 117.4653 | 0.256 | 2.067 | 0.022 | 0.414 | 0.188 | 0.156 | 0.100 | 0.122 | 0.055 |
| 87 | 241 | 117.4653 | 0.256 | 2.067 | 0.022 | 0.414 | 0.188 | 0.157 | 0.100 | 0.122 | 0.055 |
| 88 | 50 | 120.3129 | 0.263 | 2.061 | 0.022 | 0.414 | 0.186 | 0.167 | 0.106 | 0.122 | 0.055 |
| 89 | 106 | 120.3129 | 0.266 | 2.084 | 0.021 | 0.414 | 0.181 | 0.149 | 0.093 | 0.122 | 0.053 |
| 90 | 242 | 120.3129 | 0.266 | 2.085 | 0.020 | 0.414 | 0.181 | 0.150 | 0.093 | 0.122 | 0.053 |
| 91 | 43 | 121.8328 | 0.262 | 2.034 | 0.024 | 0.414 | 0.190 | 0.183 | 0.119 | 0.122 | 0.056 |
| 92 | 99 | 121.8328 | 0.262 | 2.051 | 0.022 | 0.414 | 0.186 | 0.163 | 0.103 | 0.122 | 0.055 |
| 93 | 235 | 121.8328 | 0.262 | 2.051 | 0.022 | 0.414 | 0.187 | 0.163 | 0.103 | 0.122 | 0.055 |
| 94 | 51 | 123.1945 | 0.273 | 2.079 | 0.021 | 0.414 | 0.178 | 0.160 | 0.098 | 0.122 | 0.052 |
| 95 | 107 | 123.1945 | 0.271 | 2.092 | 0.020 | 0.414 | 0.177 | 0.142 | 0.087 | 0.122 | 0.052 |
| 96 | 243 | 123.1945 | 0.271 | 2.092 | 0.019 | 0.414 | 0.177 | 0.142 | 0.087 | 0.122 | 0.052 |
| 97 | 52 | 126.1103 | 0.280 | 2.089 | 0.020 | 0.414 | 0.173 | 0.152 | 0.092 | 0.122 | 0.051 |
| 98 | 108 | 126.1103 | 0.275 | 2.097 | 0.019 | 0.414 | 0.173 | 0.134 | 0.080 | 0.122 | 0.051 |
| 99 | 244 | 126.1103 | 0.275 | 2.097 | 0.019 | 0.414 | 0.173 | 0.134 | 0.080 | 0.122 | 0.051 |
| 100 | 53 | 129.0601 | 0.284 | 2.092 | 0.019 | 0.414 | 0.170 | 0.144 | 0.085 | 0.122 | 0.050 |
| 101 | 109 | 129.0601 | 0.280 | 2.102 | 0.018 | 0.414 | 0.170 | 0.126 | 0.074 | 0.122 | 0.050 |
| 102 | 245 | 129.0601 | 0.280 | 2.102 | 0.018 | 0.414 | 0.170 | 0.126 | 0.074 | 0.122 | 0.050 |
| 103 | 2 | 129.4213 | 0.223 | 1.647 | 0.028 | 0.414 | 0.306 | 0.185 | 0.316 | 0.122 | 0.090 |
| 104 | 58 | 129.4213 | 0.223 | 1.667 | 0.026 | 0.414 | 0.297 | 0.168 | 0.295 | 0.122 | 0.087 |
| 105 | 194 | 129.4213 | 0.223 | 1.668 | 0.026 | 0.414 | 0.297 | 0.168 | 0.294 | 0.122 | 0.087 |
| 106 | 17 | 129.8252 | 0.243 | 1.779 | 0.026 | 0.414 | 0.245 | 0.187 | 0.234 | 0.122 | 0.072 |
| 107 | 73 | 129.8252 | 0.242 | 1.799 | 0.024 | 0.414 | 0.237 | 0.169 | 0.218 | 0.122 | 0.070 |
| 108 | 209 | 129.8252 | 0.242 | 1.799 | 0.024 | 0.414 | 0.236 | 0.170 | 0.217 | 0.122 | 0.070 |
| 109 | 30 | 129.9582 | 0.266 | 1.923 | 0.025 | 0.413 | 0.205 | 0.192 | 0.165 | 0.122 | 0.060 |
| 110 | 86 | 129.9582 | 0.265 | 1.945 | 0.023 | 0.414 | 0.198 | 0.173 | 0.154 | 0.122 | 0.058 |
| 111 | 222 | 129.9582 | 0.265 | 1.946 | 0.023 | 0.414 | 0.198 | 0.173 | 0.153 | 0.122 | 0.058 |
| 112 | 26 | 130.0074 | 0.257 | 1.874 | 0.025 | 0.413 | 0.217 | 0.191 | 0.186 | 0.122 | 0.064 |
| 113 | 82 | 130.0074 | 0.257 | 1.896 | 0.023 | 0.414 | 0.210 | 0.171 | 0.173 | 0.122 | 0.062 |
| 114 | 218 | 130.0074 | 0.256 | 1.896 | 0.023 | 0.414 | 0.210 | 0.172 | 0.172 | 0.122 | 0.062 |
| 115 | 35 | 130.0653 | 0.274 | 1.972 | 0.024 | 0.413 | 0.193 | 0.191 | 0.144 | 0.122 | 0.057 |
| 116 | 91 | 130.0653 | 0.273 | 1.994 | 0.022 | 0.414 | 0.187 | 0.171 | 0.134 | 0.122 | 0.055 |
| 117 | 227 | 130.0653 | 0.273 | 1.995 | 0.022 | 0.414 | 0.187 | 0.171 | 0.133 | 0.122 | 0.055 |
| 118 | 21 | 130.1006 | 0.250 | 1.827 | 0.025 | 0.414 | 0.230 | 0.189 | 0.208 | 0.122 | 0.068 |
| 119 | 77 | 130.1006 | 0.249 | 1.848 | 0.024 | 0.414 | 0.222 | 0.170 | 0.194 | 0.122 | 0.065 |
| 120 | 213 | 130.1006 | 0.249 | 1.848 | 0.024 | 0.414 | 0.222 | 0.170 | 0.193 | 0.122 | 0.065 |
| 121 | 44 | 131.7744 | 0.287 | 2.088 | 0.021 | 0.414 | 0.168 | 0.159 | 0.096 | 0.122 | 0.050 |
| 122 | 100 | 131.7744 | 0.280 | 2.085 | 0.019 | 0.414 | 0.171 | 0.141 | 0.084 | 0.122 | 0.050 |
| 123 | 236 | 131.7744 | 0.280 | 2.085 | 0.019 | 0.414 | 0.171 | 0.141 | 0.084 | 0.122 | 0.050 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 124 | 54 | 132.0441 | 0.288 | 2.095 | 0.018 | 0.414 | 0.167 | 0.135 | 0.078 | 0.122 | 0.049 |
| 125 | 110 | 132.0441 | 0.284 | 2.106 | 0.017 | 0.414 | 0.166 | 0.117 | 0.068 | 0.122 | 0.049 |
| 126 | 246 | 132.0441 | 0.284 | 2.106 | 0.017 | 0.414 | 0.166 | 0.117 | 0.068 | 0.122 | 0.049 |
| 127 | 39 | 134.8266 | 0.288 | 2.047 | 0.022 | 0.413 | 0.172 | 0.166 | 0.105 | 0.122 | 0.051 |
| 128 | 95 | 134.8266 | 0.284 | 2.055 | 0.020 | 0.414 | 0.172 | 0.148 | 0.098 | 0.122 | 0.051 |
| 129 | 231 | 134.8266 | 0.284 | 2.055 | 0.020 | 0.414 | 0.172 | 0.148 | 0.098 | 0.122 | 0.051 |
| 130 | 55 | 135.0621 | 0.292 | 2.096 | 0.017 | 0.414 | 0.164 | 0.126 | 0.071 | 0.122 | 0.048 |
| 131 | 111 | 135.0621 | 0.288 | 2.109 | 0.016 | 0.414 | 0.163 | 0.108 | 0.062 | 0.122 | 0.048 |
| 132 | 247 | 135.0621 | 0.288 | 2.109 | 0.016 | 0.414 | 0.163 | 0.109 | 0.062 | 0.122 | 0.048 |
| 133 | 56 | 138.1142 | 0.296 | 2.098 | 0.016 | 0.413 | 0.161 | 0.117 | 0.065 | 0.122 | 0.047 |
| 134 | 112 | 138.1142 | 0.292 | 2.112 | 0.015 | 0.414 | 0.161 | 0.099 | 0.056 | 0.122 | 0.047 |
| 135 | 248 | 138.1142 | 0.292 | 2.112 | 0.015 | 0.414 | 0.161 | 0.100 | 0.056 | 0.122 | 0.047 |
| 136 | 45 | 167.7286 | 0.330 | 2.066 | 0.018 | 0.413 | 0.142 | 0.041 | 0.030 | 0.121 | 0.042 |
| 137 | 101 | 167.7286 | 0.325 | 2.083 | 0.017 | 0.413 | 0.142 | 0.031 | 0.025 | 0.121 | 0.042 |
| 138 | 237 | 167.7286 | 0.325 | 2.083 | 0.017 | 0.413 | 0.142 | 0.032 | 0.024 | 0.121 | 0.042 |
| 139 | 22 | 170.3164 | 0.316 | 1.947 | 0.026 | 0.412 | 0.172 | 0.071 | 0.096 | 0.121 | 0.051 |
| 140 | 78 | 170.3164 | 0.314 | 1.962 | 0.024 | 0.412 | 0.167 | 0.060 | 0.082 | 0.121 | 0.049 |
| 141 | 214 | 170.3164 | 0.314 | 1.962 | 0.024 | 0.412 | 0.167 | 0.060 | 0.082 | 0.121 | 0.049 |
| 142 | 40 | 208.2658 | 0.360 | 2.070 | 0.014 | 0.412 | 0.126 | 0.020 | 0.018 | 0.121 | 0.037 |
| 143 | 96 | 208.2658 | 0.355 | 2.083 | 0.013 | 0.412 | 0.128 | 0.015 | 0.013 | 0.121 | 0.038 |
| 144 | 232 | 208.2658 | 0.355 | 2.083 | 0.013 | 0.412 | 0.128 | 0.015 | 0.013 | 0.121 | 0.038 |
| 145 | 31 | 215.9733 | 0.377 | 2.072 | 0.017 | 0.411 | 0.120 | 0.037 | 0.038 | 0.121 | 0.035 |
| 146 | 87 | 215.9733 | 0.370 | 2.070 | 0.016 | 0.411 | 0.123 | 0.028 | 0.030 | 0.121 | 0.036 |
| 147 | 223 | 215.9733 | 0.370 | 2.070 | 0.016 | 0.411 | 0.123 | 0.028 | 0.030 | 0.121 | 0.036 |
| 148 | 126 | 222.8766 | 0.363 | 2.087 | 0.011 | 0.412 | 0.124 | 0.012 | 0.006 | 0.121 | 0.036 |
| 149 | 260 | 222.8766 | 0.363 | 2.088 | 0.011 | 0.412 | 0.124 | 0.012 | 0.006 | 0.121 | 0.036 |
| 150 | 3 | 228.5562 | 0.341 | 1.930 | 0.022 | 0.410 | 0.186 | 0.032 | 0.078 | 0.121 | 0.055 |
| 151 | 59 | 228.5562 | 0.337 | 1.927 | 0.021 | 0.411 | 0.187 | 0.032 | 0.067 | 0.121 | 0.055 |
| 152 | 195 | 228.5562 | 0.337 | 1.927 | 0.021 | 0.411 | 0.187 | 0.032 | 0.067 | 0.121 | 0.055 |
| 153 | 12 | 254.7139 | 0.377 | 2.006 | 0.017 | 0.409 | 0.150 | 0.023 | 0.049 | 0.120 | 0.044 |
| 154 | 68 | 254.7139 | 0.373 | 2.006 | 0.016 | 0.410 | 0.150 | 0.023 | 0.039 | 0.120 | 0.044 |
| 155 | 204 | 254.7139 | 0.373 | 2.006 | 0.016 | 0.410 | 0.150 | 0.023 | 0.038 | 0.120 | 0.044 |
| 156 | 36 | 264.5698 | 0.389 | 2.069 | 0.011 | 0.410 | 0.114 | 0.009 | 0.007 | 0.121 | 0.033 |
| 157 | 92 | 264.5698 | 0.385 | 2.081 | 0.010 | 0.411 | 0.115 | 0.009 | 0.002 | 0.121 | 0.034 |
| 158 | 228 | 264.5698 | 0.385 | 2.081 | 0.010 | 0.411 | 0.115 | 0.009 | 0.002 | 0.121 | 0.034 |
| 159 | 32 | 333.6127 | 0.415 | 2.072 | 0.009 | 0.409 | 0.113 | 0.008 | 0.000 | 0.120 | 0.033 |
| 160 | 88 | 333.6127 | 0.412 | 2.083 | 0.008 | 0.409 | 0.110 | 0.008 | 0.000 | 0.120 | 0.032 |
| 161 | 224 | 333.6127 | 0.412 | 2.083 | 0.008 | 0.409 | 0.110 | 0.008 | 0.000 | 0.120 | 0.032 |
| 162 | 23 | 333.8201 | 0.422 | 2.073 | 0.011 | 0.408 | 0.117 | 0.012 | 0.012 | 0.120 | 0.034 |
| 163 | 79 | 333.8201 | 0.418 | 2.072 | 0.010 | 0.408 | 0.117 | 0.012 | 0.006 | 0.120 | 0.034 |
| 164 | 215 | 333.8201 | 0.418 | 2.072 | 0.010 | 0.408 | 0.117 | 0.012 | 0.006 | 0.120 | 0.034 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 165 | 123 | 357.0172 | 0.419 | 2.088 | 0.008 | 0.409 | 0.108 | 0.007 | 0.000 | 0.120 | 0.032 |
| 166 | 257 | 357.0172 | 0.418 | 2.088 | 0.008 | 0.409 | 0.108 | 0.007 | 0.000 | 0.120 | 0.032 |
| 167 | 27 | 416.6143 | 0.434 | 2.073 | 0.008 | 0.407 | 0.113 | 0.007 | 0.000 | 0.120 | 0.033 |
| 168 | 83 | 416.6143 | 0.432 | 2.085 | 0.007 | 0.408 | 0.109 | 0.007 | 0.000 | 0.120 | 0.032 |
| 169 | 219 | 416.6143 | 0.432 | 2.085 | 0.007 | 0.408 | 0.109 | 0.007 | 0.000 | 0.120 | 0.032 |
| 170 | 13 | 499.2391 | 0.448 | 2.075 | 0.010 | 0.404 | 0.116 | 0.010 | 0.000 | 0.119 | 0.034 |
| 171 | 69 | 499.2391 | 0.446 | 2.076 | 0.009 | 0.405 | 0.115 | 0.010 | 0.000 | 0.119 | 0.034 |
| 172 | 205 | 499.2391 | 0.446 | 2.076 | 0.009 | 0.405 | 0.115 | 0.010 | 0.000 | 0.119 | 0.034 |
| 173 | 24 | 503.8640 | 0.446 | 2.075 | 0.007 | 0.406 | 0.113 | 0.007 | 0.000 | 0.119 | 0.033 |
| 174 | 80 | 503.8640 | 0.445 | 2.085 | 0.007 | 0.406 | 0.109 | 0.007 | 0.000 | 0.119 | 0.032 |
| 175 | 216 | 503.8640 | 0.445 | 2.085 | 0.007 | 0.406 | 0.109 | 0.007 | 0.000 | 0.119 | 0.032 |
| 176 | 4 | 514.2514 | 0.445 | 2.063 | 0.011 | 0.403 | 0.122 | 0.014 | 0.004 | 0.118 | 0.036 |
| 177 | 60 | 514.2514 | 0.443 | 2.062 | 0.011 | 0.404 | 0.123 | 0.014 | 0.000 | 0.119 | 0.036 |
| 178 | 196 | 514.2514 | 0.443 | 2.062 | 0.011 | 0.404 | 0.123 | 0.014 | 0.000 | 0.119 | 0.036 |
| 179 | 120 | 551.8250 | 0.449 | 2.088 | 0.007 | 0.406 | 0.108 | 0.009 | 0.000 | 0.119 | 0.032 |
| 180 | 254 | 551.8250 | 0.449 | 2.088 | 0.007 | 0.406 | 0.108 | 0.008 | 0.000 | 0.119 | 0.032 |
| 181 | 18 | 618.5337 | 0.455 | 2.076 | 0.007 | 0.404 | 0.113 | 0.011 | 0.000 | 0.119 | 0.033 |
| 182 | 74 | 618.5337 | 0.454 | 2.085 | 0.007 | 0.404 | 0.109 | 0.013 | 0.000 | 0.119 | 0.032 |
| 183 | 210 | 618.5337 | 0.454 | 2.085 | 0.007 | 0.404 | 0.109 | 0.012 | 0.000 | 0.119 | 0.032 |
| 184 | 5 | 699.9532 | 0.455 | 2.071 | 0.009 | 0.400 | 0.117 | 0.011 | 0.000 | 0.118 | 0.034 |
| 185 | 61 | 699.9532 | 0.454 | 2.071 | 0.008 | 0.401 | 0.117 | 0.014 | 0.000 | 0.118 | 0.034 |
| 186 | 197 | 699.9532 | 0.454 | 2.071 | 0.008 | 0.401 | 0.117 | 0.013 | 0.000 | 0.118 | 0.034 |
| 187 | 14 | 771.1717 | 0.461 | 2.074 | 0.007 | 0.401 | 0.114 | 0.018 | 0.000 | 0.118 | 0.034 |
| 188 | 70 | 771.1717 | 0.460 | 2.084 | 0.006 | 0.402 | 0.110 | 0.021 | 0.000 | 0.118 | 0.032 |
| 189 | 206 | 771.1717 | 0.460 | 2.084 | 0.006 | 0.402 | 0.110 | 0.020 | 0.000 | 0.118 | 0.032 |
| 190 | 117 | 825.2729 | 0.460 | 2.084 | 0.006 | 0.402 | 0.110 | 0.023 | 0.000 | 0.118 | 0.032 |
| 191 | 252 | 825.2729 | 0.460 | 2.084 | 0.006 | 0.402 | 0.110 | 0.022 | 0.000 | 0.118 | 0.032 |
| 192 | 9 | 954.4603 | 0.456 | 2.059 | 0.006 | 0.399 | 0.121 | 0.023 | 0.000 | 0.117 | 0.036 |
| 193 | 65 | 954.4603 | 0.455 | 2.069 | 0.006 | 0.400 | 0.116 | 0.027 | 0.000 | 0.118 | 0.034 |
| 194 | 201 | 954.4603 | 0.455 | 2.069 | 0.006 | 0.400 | 0.116 | 0.026 | 0.000 | 0.118 | 0.034 |
| 195 | 6 | 1106.2120 | 0.451 | 2.045 | 0.006 | 0.399 | 0.127 | 0.026 | 0.000 | 0.117 | 0.037 |
| 196 | 62 | 1106.2120 | 0.449 | 2.055 | 0.006 | 0.399 | 0.121 | 0.031 | 0.000 | 0.117 | 0.036 |
| 197 | 198 | 1106.2120 | 0.449 | 2.055 | 0.006 | 0.399 | 0.121 | 0.030 | 0.000 | 0.117 | 0.036 |
| 198 | 114 | 1157.0650 | 0.447 | 2.051 | 0.005 | 0.399 | 0.123 | 0.032 | 0.000 | 0.117 | 0.036 |
| 199 | 249 | 1157.0650 | 0.447 | 2.051 | 0.005 | 0.399 | 0.123 | 0.031 | 0.000 | 0.117 | 0.036 |

08/29/96

13:10

513 476 7302

AFIT/ENA WPAFB

002

D.3 Lateral Maximum P_{cmd} Step Input Time Response (Healthy)

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 1 | 119 | 65.4696 | 9.848 | 84.197 | 2.448 | 18.191 | 11.659 | 20.271 | 17.555 | 5.348 | 3.428 |
| 2 | 253 | 65.4696 | 9.843 | 84.215 | 2.442 | 18.191 | 11.657 | 20.255 | 17.516 | 5.348 | 3.427 |
| 3 | 118 | 65.5666 | 9.856 | 83.255 | 2.488 | 18.218 | 11.866 | 20.329 | 19.892 | 5.356 | 3.488 |
| 4 | 122 | 67.0399 | 10.245 | 88.908 | 2.360 | 18.654 | 11.386 | 20.092 | 14.134 | 5.484 | 3.348 |
| 5 | 256 | 67.0399 | 10.240 | 88.928 | 2.354 | 18.654 | 11.384 | 20.082 | 14.090 | 5.484 | 3.347 |
| 6 | 121 | 67.4267 | 10.377 | 88.645 | 2.394 | 18.765 | 11.518 | 20.253 | 15.110 | 5.517 | 3.386 |
| 7 | 255 | 67.4267 | 10.372 | 88.665 | 2.388 | 18.764 | 11.515 | 20.242 | 15.079 | 5.517 | 3.386 |
| 8 | 124 | 67.6717 | 10.362 | 90.844 | 2.316 | 18.841 | 11.310 | 19.907 | 13.382 | 5.539 | 3.325 |
| 9 | 116 | 68.8746 | 10.785 | 88.114 | 2.518 | 19.180 | 12.037 | 20.565 | 21.568 | 5.639 | 3.539 |
| 10 | 251 | 68.8746 | 10.779 | 88.130 | 2.512 | 19.180 | 12.034 | 20.553 | 21.519 | 5.639 | 3.538 |
| 11 | 115 | 70.9929 | 11.365 | 90.623 | 2.553 | 19.796 | 12.271 | 20.658 | 23.515 | 5.820 | 3.608 |
| 12 | 10 | 74.2746 | 12.197 | 94.991 | 2.620 | 20.743 | 12.859 | 22.335 | 21.664 | 6.098 | 3.781 |
| 13 | 66 | 74.2746 | 12.382 | 97.560 | 2.491 | 20.753 | 12.005 | 20.858 | 20.522 | 6.101 | 3.530 |
| 14 | 202 | 74.2746 | 12.376 | 97.574 | 2.485 | 20.752 | 12.003 | 20.851 | 20.475 | 6.101 | 3.529 |
| 15 | 113 | 75.5664 | 12.685 | 97.403 | 2.563 | 21.125 | 12.491 | 20.815 | 24.405 | 6.211 | 3.672 |
| 16 | 250 | 77.0323 | 13.160 | 100.912 | 2.511 | 21.552 | 12.271 | 20.921 | 22.196 | 6.336 | 3.608 |
| 17 | 258 | 77.2143 | 12.984 | 106.967 | 2.189 | 21.621 | 11.555 | 19.963 | 11.681 | 6.357 | 3.397 |
| 18 | 125 | 77.2914 | 12.944 | 108.249 | 2.145 | 21.646 | 11.473 | 19.710 | 11.416 | 6.364 | 3.373 |
| 19 | 259 | 77.2914 | 12.938 | 108.268 | 2.140 | 21.646 | 11.471 | 19.714 | 11.372 | 6.364 | 3.373 |
| 20 | 37 | 80.2356 | 13.851 | 112.388 | 2.212 | 22.492 | 11.795 | 21.157 | 11.725 | 6.613 | 3.468 |
| 21 | 93 | 80.2356 | 14.161 | 114.471 | 2.128 | 22.497 | 11.196 | 20.043 | 11.124 | 6.614 | 3.292 |
| 22 | 229 | 80.2356 | 14.155 | 114.490 | 2.123 | 22.496 | 11.194 | 20.053 | 11.083 | 6.614 | 3.291 |
| 23 | 15 | 80.3692 | 13.968 | 105.949 | 2.461 | 22.515 | 12.754 | 22.166 | 18.160 | 6.619 | 3.750 |
| 24 | 71 | 80.3692 | 14.100 | 107.763 | 2.325 | 22.526 | 12.096 | 20.537 | 17.329 | 6.623 | 3.556 |
| 25 | 207 | 80.3692 | 14.094 | 107.778 | 2.320 | 22.525 | 12.093 | 20.541 | 17.289 | 6.622 | 3.555 |
| 26 | 33 | 80.5349 | 13.972 | 111.390 | 2.262 | 22.575 | 11.974 | 21.471 | 12.039 | 6.637 | 3.520 |
| 27 | 89 | 80.5349 | 14.244 | 113.435 | 2.168 | 22.582 | 11.358 | 20.221 | 11.342 | 6.639 | 3.339 |
| 28 | 225 | 80.5349 | 14.238 | 113.452 | 2.163 | 22.581 | 11.356 | 20.228 | 11.298 | 6.639 | 3.339 |
| 29 | 28 | 81.4969 | 14.353 | 111.948 | 2.304 | 22.851 | 12.086 | 21.798 | 12.404 | 6.718 | 3.553 |
| 30 | 84 | 81.4969 | 14.586 | 113.878 | 2.199 | 22.858 | 11.473 | 20.410 | 12.140 | 6.720 | 3.373 |
| 31 | 220 | 81.4969 | 14.580 | 113.894 | 2.194 | 22.858 | 11.472 | 20.418 | 12.116 | 6.720 | 3.373 |
| 32 | 1 | 82.2802 | 14.442 | 105.752 | 2.655 | 23.063 | 13.542 | 22.593 | 24.513 | 6.780 | 3.981 |
| 33 | 57 | 82.2802 | 14.532 | 107.590 | 2.500 | 23.075 | 12.813 | 20.903 | 23.128 | 6.784 | 3.767 |
| 34 | 193 | 82.2802 | 14.527 | 107.603 | 2.494 | 23.075 | 12.809 | 20.902 | 23.072 | 6.784 | 3.766 |
| 35 | 7 | 83.3181 | 14.811 | 108.634 | 2.602 | 23.366 | 13.268 | 22.692 | 22.403 | 6.870 | 3.901 |
| 36 | 63 | 83.3181 | 14.915 | 110.461 | 2.456 | 23.378 | 12.566 | 21.020 | 21.219 | 6.873 | 3.694 |
| 37 | 199 | 83.3181 | 14.910 | 110.474 | 2.450 | 23.378 | 12.563 | 21.022 | 21.168 | 6.873 | 3.693 |
| 38 | 19 | 83.4550 | 14.970 | 112.530 | 2.377 | 23.411 | 12.498 | 22.169 | 15.752 | 6.883 | 3.674 |
| 39 | 75 | 83.4550 | 15.141 | 114.275 | 2.253 | 23.422 | 11.876 | 20.575 | 15.124 | 6.886 | 3.492 |
| 40 | 211 | 83.4550 | 15.136 | 114.289 | 2.247 | 23.421 | 11.873 | 20.583 | 15.089 | 6.886 | 3.491 |
| 41 | 25 | 83.7192 | 15.109 | 114.507 | 2.329 | 23.490 | 12.236 | 22.088 | 13.921 | 6.906 | 3.597 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 42 | 81 | 83.7192 | 15.321 | 116.333 | 2.216 | 23.500 | 11.620 | 20.581 | 13.476 | 6.909 | 3.416 |
| 43 | 217 | 83.7192 | 15.315 | 116.348 | 2.211 | 23.499 | 11.618 | 20.591 | 13.446 | 6.909 | 3.416 |
| 44 | 34 | 87.3860 | 16.738 | 124.819 | 2.213 | 24.550 | 11.474 | 22.129 | 11.317 | 7.218 | 3.373 |
| 45 | 90 | 87.3860 | 17.033 | 126.492 | 2.113 | 24.558 | 10.931 | 20.735 | 10.635 | 7.220 | 3.214 |
| 46 | 226 | 87.3860 | 17.027 | 126.508 | 2.108 | 24.557 | 10.929 | 20.757 | 10.598 | 7.220 | 3.213 |
| 47 | 127 | 88.7159 | 17.945 | 133.285 | 1.983 | 24.949 | 10.249 | 19.803 | 9.788 | 7.335 | 3.013 |
| 48 | 261 | 88.7159 | 17.939 | 133.297 | 1.979 | 24.949 | 10.250 | 19.828 | 9.758 | 7.335 | 3.014 |
| 49 | 38 | 89.3983 | 17.932 | 131.116 | 2.147 | 25.124 | 10.908 | 22.296 | 10.879 | 7.387 | 3.207 |
| 50 | 94 | 89.3983 | 18.189 | 132.482 | 2.050 | 25.134 | 10.466 | 20.844 | 10.232 | 7.390 | 3.077 |
| 51 | 230 | 89.3983 | 18.182 | 132.495 | 2.045 | 25.134 | 10.466 | 20.869 | 10.200 | 7.389 | 3.077 |
| 52 | 11 | 91.6970 | 17.509 | 123.894 | 2.484 | 25.792 | 13.015 | 23.115 | 18.999 | 7.583 | 3.827 |
| 53 | 67 | 91.6970 | 17.606 | 125.154 | 2.332 | 25.806 | 12.462 | 21.257 | 17.980 | 7.587 | 3.664 |
| 54 | 203 | 91.6970 | 17.600 | 125.164 | 2.326 | 25.806 | 12.459 | 21.270 | 17.937 | 7.587 | 3.663 |
| 55 | 41 | 94.3473 | 19.919 | 141.797 | 2.019 | 26.570 | 10.496 | 20.992 | 9.822 | 7.812 | 3.086 |
| 56 | 97 | 94.3473 | 20.029 | 142.987 | 1.919 | 26.586 | 10.191 | 19.344 | 9.127 | 7.816 | 2.996 |
| 57 | 233 | 94.3473 | 20.024 | 142.995 | 1.915 | 26.586 | 10.193 | 19.374 | 9.101 | 7.816 | 2.997 |
| 58 | 262 | 101.0962 | 22.090 | 155.562 | 1.727 | 28.574 | 10.318 | 16.814 | 7.548 | 8.401 | 3.034 |
| 59 | 16 | 102.4478 | 21.142 | 141.631 | 2.227 | 28.896 | 12.890 | 22.153 | 15.268 | 8.495 | 3.790 |
| 60 | 72 | 102.4478 | 21.117 | 142.319 | 2.091 | 28.919 | 12.529 | 20.149 | 14.427 | 8.502 | 3.684 |
| 61 | 208 | 102.4478 | 21.111 | 142.326 | 2.086 | 28.918 | 12.527 | 20.182 | 14.391 | 8.502 | 3.683 |
| 62 | 263 | 103.7392 | 23.297 | 160.097 | 1.698 | 29.337 | 10.244 | 16.648 | 7.300 | 8.625 | 3.012 |
| 63 | 42 | 106.1299 | 24.461 | 161.457 | 1.899 | 29.986 | 10.416 | 20.145 | 8.621 | 8.816 | 3.062 |
| 64 | 98 | 106.1299 | 24.567 | 162.242 | 1.781 | 30.004 | 10.217 | 18.326 | 7.860 | 8.821 | 3.004 |
| 65 | 234 | 106.1299 | 24.565 | 162.248 | 1.776 | 30.003 | 10.218 | 18.369 | 7.843 | 8.821 | 3.004 |
| 66 | 264 | 106.4162 | 24.628 | 164.670 | 1.667 | 30.108 | 10.133 | 16.484 | 7.051 | 8.852 | 2.979 |
| 67 | 20 | 109.0025 | 23.811 | 154.280 | 2.118 | 30.786 | 12.426 | 22.041 | 12.911 | 9.051 | 3.653 |
| 68 | 76 | 109.0025 | 23.779 | 154.818 | 1.989 | 30.811 | 12.140 | 20.014 | 12.191 | 9.058 | 3.569 |
| 69 | 212 | 109.0025 | 23.772 | 154.824 | 1.985 | 30.810 | 12.139 | 20.056 | 12.160 | 9.058 | 3.569 |
| 70 | 46 | 109.1273 | 25.631 | 168.491 | 1.764 | 30.880 | 10.280 | 17.941 | 7.548 | 9.079 | 3.022 |
| 71 | 102 | 109.1273 | 26.008 | 169.186 | 1.639 | 30.888 | 10.031 | 16.252 | 6.815 | 9.081 | 2.949 |
| 72 | 238 | 109.1273 | 26.011 | 169.190 | 1.635 | 30.888 | 10.030 | 16.302 | 6.803 | 9.081 | 2.949 |
| 73 | 29 | 110.1905 | 25.338 | 161.212 | 2.037 | 31.121 | 11.354 | 22.280 | 10.065 | 9.150 | 3.338 |
| 74 | 85 | 110.1905 | 25.349 | 161.816 | 1.918 | 31.146 | 11.112 | 20.305 | 9.532 | 9.157 | 3.267 |
| 75 | 221 | 110.1905 | 25.342 | 161.821 | 1.914 | 31.145 | 11.113 | 20.353 | 9.507 | 9.157 | 3.267 |
| 76 | 8 | 110.9265 | 23.105 | 150.152 | 2.274 | 31.344 | 14.345 | 22.020 | 18.024 | 9.215 | 4.217 |
| 77 | 64 | 110.9265 | 23.002 | 150.444 | 2.120 | 31.371 | 14.019 | 19.806 | 16.875 | 9.223 | 4.122 |
| 78 | 200 | 110.9265 | 22.996 | 150.450 | 2.116 | 31.371 | 14.016 | 19.840 | 16.833 | 9.223 | 4.121 |
| 79 | 47 | 111.8726 | 27.139 | 172.989 | 1.721 | 31.666 | 10.118 | 17.747 | 7.275 | 9.310 | 2.975 |
| 80 | 103 | 111.8726 | 27.500 | 173.490 | 1.597 | 31.674 | 9.907 | 16.045 | 6.561 | 9.312 | 2.913 |
| 81 | 239 | 111.8726 | 27.504 | 173.493 | 1.593 | 31.673 | 9.906 | 16.098 | 6.551 | 9.312 | 2.912 |
| 82 | 48 | 114.6519 | 28.714 | 177.459 | 1.675 | 32.459 | 9.958 | 17.545 | 7.002 | 9.543 | 2.928 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 83 | 104 | 114.6519 | 29.072 | 177.821 | 1.554 | 32.468 | 9.776 | 15.820 | 6.307 | 9.545 | 2.874 |
| 84 | 240 | 114.6519 | 29.076 | 177.823 | 1.550 | 32.467 | 9.774 | 15.877 | 6.300 | 9.545 | 2.874 |
| 85 | 49 | 117.4653 | 30.357 | 181.923 | 1.628 | 33.260 | 9.798 | 17.335 | 6.730 | 9.778 | 2.881 |
| 86 | 105 | 117.4653 | 30.726 | 182.191 | 1.509 | 33.268 | 9.638 | 15.584 | 6.053 | 9.781 | 2.834 |
| 87 | 241 | 117.4653 | 30.730 | 182.192 | 1.506 | 33.267 | 9.636 | 15.649 | 6.048 | 9.781 | 2.833 |
| 88 | 50 | 120.3129 | 32.071 | 186.403 | 1.579 | 34.067 | 9.639 | 17.104 | 6.459 | 10.016 | 2.834 |
| 89 | 106 | 120.3129 | 32.463 | 186.608 | 1.464 | 34.076 | 9.496 | 15.332 | 5.800 | 10.018 | 2.792 |
| 90 | 242 | 120.3129 | 32.468 | 186.609 | 1.461 | 34.075 | 9.494 | 15.401 | 5.797 | 10.018 | 2.791 |
| 91 | 43 | 121.8328 | 32.150 | 187.673 | 1.726 | 34.497 | 9.917 | 18.936 | 7.174 | 10.142 | 2.916 |
| 92 | 99 | 121.8328 | 32.262 | 187.798 | 1.599 | 34.514 | 9.857 | 16.950 | 6.435 | 10.147 | 2.898 |
| 93 | 235 | 121.8328 | 32.261 | 187.799 | 1.595 | 34.514 | 9.858 | 17.016 | 6.431 | 10.147 | 2.898 |
| 94 | 51 | 123.1945 | 33.858 | 190.917 | 1.529 | 34.881 | 9.479 | 16.868 | 6.191 | 10.255 | 2.787 |
| 95 | 107 | 123.1945 | 33.815 | 190.960 | 1.430 | 34.904 | 9.522 | 14.949 | 5.548 | 10.262 | 2.800 |
| 96 | 243 | 123.1945 | 33.810 | 190.958 | 1.426 | 34.903 | 9.524 | 15.021 | 5.548 | 10.261 | 2.800 |
| 97 | 52 | 126.1103 | 35.441 | 195.391 | 1.488 | 35.710 | 9.421 | 16.563 | 5.938 | 10.499 | 2.770 |
| 98 | 108 | 126.1103 | 35.139 | 195.339 | 1.394 | 35.742 | 9.574 | 14.489 | 5.279 | 10.508 | 2.815 |
| 99 | 244 | 126.1103 | 35.134 | 195.336 | 1.390 | 35.742 | 9.575 | 14.564 | 5.281 | 10.508 | 2.815 |
| 100 | 53 | 129.0601 | 36.745 | 199.775 | 1.447 | 36.557 | 9.479 | 16.066 | 5.651 | 10.748 | 2.787 |
| 101 | 109 | 129.0601 | 36.474 | 199.757 | 1.355 | 36.591 | 9.633 | 13.945 | 4.992 | 10.758 | 2.832 |
| 102 | 245 | 129.0601 | 36.469 | 199.754 | 1.352 | 36.590 | 9.635 | 14.021 | 4.995 | 10.757 | 2.833 |
| 103 | 2 | 129.4213 | 29.100 | 176.673 | 2.153 | 36.662 | 16.034 | 20.935 | 17.144 | 10.779 | 4.714 |
| 104 | 58 | 129.4213 | 29.223 | 177.437 | 2.027 | 36.692 | 15.724 | 18.781 | 16.144 | 10.787 | 4.623 |
| 105 | 194 | 129.4213 | 29.217 | 177.444 | 2.024 | 36.691 | 15.723 | 18.842 | 16.104 | 10.787 | 4.623 |
| 106 | 17 | 129.8252 | 31.467 | 185.478 | 1.989 | 36.763 | 12.801 | 21.228 | 12.414 | 10.808 | 3.764 |
| 107 | 73 | 129.8252 | 31.565 | 186.120 | 1.868 | 36.794 | 12.471 | 19.056 | 11.680 | 10.817 | 3.667 |
| 108 | 209 | 129.8252 | 31.559 | 186.125 | 1.864 | 36.793 | 12.470 | 19.126 | 11.650 | 10.817 | 3.666 |
| 109 | 30 | 129.9582 | 34.174 | 193.790 | 1.877 | 36.775 | 10.873 | 21.792 | 8.559 | 10.812 | 3.197 |
| 110 | 86 | 129.9582 | 34.274 | 194.316 | 1.754 | 36.807 | 10.703 | 19.564 | 8.022 | 10.821 | 3.147 |
| 111 | 222 | 129.9582 | 34.267 | 194.319 | 1.751 | 36.806 | 10.706 | 19.648 | 8.001 | 10.821 | 3.147 |
| 112 | 26 | 130.0074 | 33.237 | 191.252 | 1.912 | 36.801 | 11.473 | 21.613 | 9.730 | 10.819 | 3.373 |
| 113 | 82 | 130.0074 | 33.332 | 191.815 | 1.790 | 36.832 | 11.252 | 19.397 | 9.132 | 10.829 | 3.308 |
| 114 | 218 | 130.0074 | 33.326 | 191.819 | 1.787 | 36.831 | 11.254 | 19.475 | 9.107 | 10.828 | 3.309 |
| 115 | 35 | 130.0653 | 35.155 | 196.357 | 1.829 | 36.799 | 10.345 | 21.599 | 7.754 | 10.819 | 3.041 |
| 116 | 91 | 130.0653 | 35.260 | 196.841 | 1.707 | 36.830 | 10.231 | 19.400 | 7.000 | 10.828 | 3.008 |
| 117 | 227 | 130.0653 | 35.253 | 196.844 | 1.704 | 36.830 | 10.235 | 19.488 | 6.997 | 10.828 | 3.009 |
| 118 | 21 | 130.1006 | 32.407 | 188.709 | 1.946 | 36.836 | 12.101 | 21.402 | 10.985 | 10.830 | 3.558 |
| 119 | 77 | 130.1006 | 32.502 | 189.305 | 1.825 | 36.867 | 11.830 | 19.198 | 10.320 | 10.839 | 3.478 |
| 120 | 213 | 130.1006 | 32.495 | 189.309 | 1.821 | 36.866 | 11.831 | 19.272 | 10.293 | 10.839 | 3.478 |
| 121 | 44 | 131.7744 | 37.545 | 203.620 | 1.609 | 37.331 | 9.692 | 18.025 | 6.332 | 10.975 | 2.849 |
| 122 | 100 | 131.7744 | 37.068 | 203.328 | 1.502 | 37.364 | 9.882 | 16.005 | 5.672 | 10.985 | 2.905 |
| 123 | 236 | 131.7744 | 37.062 | 203.326 | 1.499 | 37.363 | 9.884 | 16.092 | 5.674 | 10.985 | 2.906 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 124 | 54 | 132.0441 | 38.058 | 204.199 | 1.404 | 37.413 | 9.545 | 15.484 | 5.345 | 10.999 | 2.806 |
| 125 | 110 | 132.0441 | 37.821 | 204.218 | 1.314 | 37.449 | 9.702 | 13.314 | 4.685 | 11.010 | 2.852 |
| 126 | 246 | 132.0441 | 37.815 | 204.215 | 1.311 | 37.448 | 9.703 | 13.392 | 4.690 | 11.010 | 2.853 |
| 127 | 39 | 134.8266 | 38.283 | 206.404 | 1.683 | 38.182 | 9.910 | 19.413 | 6.753 | 11.226 | 2.913 |
| 128 | 95 | 134.8266 | 38.089 | 206.416 | 1.571 | 38.215 | 10.004 | 17.340 | 6.066 | 11.235 | 2.941 |
| 129 | 231 | 134.8266 | 38.083 | 206.416 | 1.568 | 38.214 | 10.007 | 17.432 | 6.068 | 11.235 | 2.942 |
| 130 | 55 | 135.0621 | 39.379 | 208.663 | 1.359 | 38.280 | 9.620 | 14.809 | 5.021 | 11.254 | 2.828 |
| 131 | 111 | 135.0621 | 39.178 | 208.725 | 1.272 | 38.318 | 9.779 | 12.597 | 4.361 | 11.265 | 2.875 |
| 132 | 247 | 135.0621 | 39.172 | 208.722 | 1.269 | 38.317 | 9.780 | 12.680 | 4.368 | 11.265 | 2.875 |
| 133 | 56 | 138.1142 | 40.710 | 213.170 | 1.313 | 39.156 | 9.702 | 14.042 | 4.681 | 11.512 | 2.852 |
| 134 | 112 | 138.1142 | 40.545 | 213.280 | 1.227 | 39.196 | 9.865 | 11.801 | 4.021 | 11.524 | 2.900 |
| 135 | 248 | 138.1142 | 40.540 | 213.277 | 1.224 | 39.195 | 9.866 | 11.888 | 4.029 | 11.523 | 2.901 |
| 136 | 45 | 167.7286 | 53.348 | 256.314 | 1.967 | 47.614 | 10.509 | 5.932 | 2.018 | 13.999 | 3.090 |
| 137 | 101 | 167.7286 | 53.172 | 256.843 | 1.842 | 47.672 | 10.758 | 4.547 | 1.682 | 14.015 | 3.163 |
| 138 | 237 | 167.7286 | 53.160 | 256.845 | 1.837 | 47.671 | 10.757 | 4.629 | 1.669 | 14.015 | 3.163 |
| 139 | 22 | 170.3164 | 51.241 | 252.886 | 2.769 | 48.229 | 11.929 | 10.740 | 7.114 | 14.179 | 3.507 |
| 140 | 78 | 170.3164 | 51.259 | 253.527 | 2.560 | 48.283 | 11.714 | 9.151 | 6.228 | 14.195 | 3.444 |
| 141 | 214 | 170.3164 | 51.247 | 253.532 | 2.554 | 48.282 | 11.713 | 9.247 | 6.201 | 14.195 | 3.444 |
| 142 | 40 | 208.2658 | 70.319 | 318.593 | 1.915 | 59.123 | 11.895 | 3.679 | 1.559 | 17.382 | 3.497 |
| 143 | 96 | 208.2658 | 70.133 | 319.242 | 1.795 | 59.212 | 12.203 | 2.396 | 1.166 | 17.408 | 3.588 |
| 144 | 232 | 208.2658 | 70.119 | 319.243 | 1.790 | 59.210 | 12.201 | 2.462 | 1.150 | 17.408 | 3.587 |
| 145 | 31 | 215.9733 | 74.471 | 330.990 | 2.365 | 60.000 | 11.532 | 7.218 | 3.503 | 17.957 | 3.390 |
| 146 | 87 | 215.9733 | 73.852 | 330.579 | 2.179 | 60.000 | 11.850 | 5.454 | 2.858 | 17.988 | 3.484 |
| 147 | 223 | 215.9733 | 73.838 | 330.578 | 2.173 | 60.000 | 11.848 | 5.579 | 2.837 | 17.988 | 3.483 |
| 148 | 126 | 222.8766 | 76.324 | 342.121 | 1.683 | 60.000 | 12.814 | 1.124 | 0.605 | 18.636 | 3.767 |
| 149 | 260 | 222.8766 | 76.310 | 342.122 | 1.678 | 60.000 | 12.812 | 1.128 | 0.590 | 18.635 | 3.767 |
| 150 | 3 | 228.5562 | 72.151 | 336.858 | 3.085 | 60.000 | 17.869 | 6.587 | 8.013 | 18.983 | 5.253 |
| 151 | 59 | 228.5562 | 71.801 | 336.396 | 2.951 | 60.000 | 17.887 | 4.851 | 7.097 | 19.015 | 5.259 |
| 152 | 195 | 228.5562 | 71.791 | 336.399 | 2.946 | 60.000 | 17.886 | 4.958 | 7.059 | 19.015 | 5.259 |
| 153 | 12 | 254.7139 | 85.195 | 378.355 | 2.763 | 60.000 | 15.802 | 5.401 | 5.530 | 20.805 | 4.646 |
| 154 | 68 | 254.7139 | 84.897 | 378.188 | 2.593 | 60.000 | 15.778 | 3.614 | 4.505 | 20.846 | 4.639 |
| 155 | 204 | 254.7139 | 84.886 | 378.190 | 2.588 | 60.000 | 15.777 | 3.713 | 4.473 | 20.845 | 4.639 |
| 156 | 36 | 264.5698 | 89.483 | 388.044 | 1.831 | 60.000 | 13.345 | 1.439 | 0.736 | 21.109 | 3.923 |
| 157 | 92 | 264.5698 | 89.508 | 389.041 | 1.710 | 60.000 | 13.671 | 1.054 | 0.262 | 21.146 | 4.019 |
| 158 | 228 | 264.5698 | 89.494 | 389.042 | 1.706 | 60.000 | 13.669 | 1.052 | 0.246 | 21.145 | 4.019 |
| 159 | 32 | 333.6127 | 98.002 | 413.065 | 1.640 | 60.000 | 13.187 | 2.121 | 0.000 | 22.341 | 3.877 |
| 160 | 88 | 333.6127 | 98.198 | 414.248 | 1.541 | 60.000 | 13.491 | 2.392 | 0.000 | 22.387 | 3.966 |
| 161 | 224 | 333.6127 | 98.188 | 414.248 | 1.538 | 60.000 | 13.488 | 2.183 | 0.000 | 22.386 | 3.965 |
| 162 | 23 | 333.8201 | 98.357 | 413.505 | 2.032 | 60.000 | 13.269 | 1.598 | 1.425 | 22.227 | 3.901 |
| 163 | 79 | 333.8201 | 98.072 | 413.315 | 1.910 | 60.000 | 13.293 | 1.482 | 0.757 | 22.280 | 3.908 |
| 164 | 215 | 333.8201 | 98.064 | 413.315 | 1.906 | 60.000 | 13.294 | 1.446 | 0.737 | 22.279 | 3.908 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 165 | 123 | 357.0172 | 100.992 | 423.158 | 1.451 | 60.000 | 13.586 | 3.321 | 0.000 | 22.823 | 3.994 |
| 166 | 257 | 357.0172 | 100.984 | 423.159 | 1.448 | 60.000 | 13.583 | 3.094 | 0.000 | 22.822 | 3.993 |
| 167 | 27 | 416.6143 | 105.294 | 437.079 | 1.547 | 60.000 | 13.600 | 4.856 | 0.000 | 23.494 | 3.998 |
| 168 | 83 | 416.6143 | 105.668 | 438.483 | 1.466 | 60.000 | 13.404 | 5.426 | 0.000 | 23.547 | 3.941 |
| 169 | 219 | 416.6143 | 105.664 | 438.484 | 1.463 | 60.000 | 13.400 | 5.153 | 0.000 | 23.546 | 3.940 |
| 170 | 13 | 499.2391 | 106.162 | 437.211 | 1.783 | 60.000 | 13.985 | 6.316 | 0.000 | 23.271 | 4.111 |
| 171 | 69 | 499.2391 | 106.077 | 437.212 | 1.711 | 60.000 | 13.945 | 7.235 | 0.000 | 23.316 | 4.100 |
| 172 | 205 | 499.2391 | 106.077 | 437.212 | 1.709 | 60.000 | 13.945 | 6.902 | 0.000 | 23.315 | 4.100 |
| 173 | 24 | 503.8640 | 106.179 | 437.078 | 1.454 | 60.000 | 13.634 | 7.613 | 0.000 | 23.373 | 4.008 |
| 174 | 80 | 503.8640 | 106.474 | 438.289 | 1.387 | 60.000 | 13.240 | 8.336 | 0.000 | 23.413 | 3.893 |
| 175 | 216 | 503.8640 | 106.474 | 438.290 | 1.385 | 60.000 | 13.240 | 8.027 | 0.000 | 23.412 | 3.893 |
| 176 | 4 | 514.2514 | 105.443 | 435.827 | 2.039 | 60.000 | 14.838 | 5.728 | 0.607 | 23.187 | 4.362 |
| 177 | 60 | 514.2514 | 105.261 | 435.588 | 1.950 | 60.000 | 14.875 | 6.581 | 0.000 | 23.236 | 4.373 |
| 178 | 196 | 514.2514 | 105.260 | 435.588 | 1.947 | 60.000 | 14.875 | 6.236 | 0.000 | 23.235 | 4.373 |
| 179 | 120 | 551.8250 | 106.868 | 438.548 | 1.274 | 60.000 | 13.094 | 9.973 | 0.000 | 23.380 | 3.850 |
| 180 | 254 | 551.8250 | 106.868 | 438.548 | 1.272 | 60.000 | 13.093 | 9.653 | 0.000 | 23.379 | 3.849 |
| 181 | 18 | 618.5337 | 106.840 | 436.967 | 1.366 | 60.000 | 13.685 | 11.233 | 0.000 | 23.234 | 4.024 |
| 182 | 74 | 618.5337 | 107.072 | 438.139 | 1.307 | 60.000 | 13.274 | 12.078 | 0.000 | 23.280 | 3.903 |
| 183 | 210 | 618.5337 | 107.072 | 438.139 | 1.305 | 60.000 | 13.274 | 11.729 | 0.000 | 23.279 | 3.903 |
| 184 | 5 | 699.9532 | 106.595 | 436.452 | 1.623 | 60.000 | 14.215 | 12.314 | 0.000 | 23.025 | 4.179 |
| 185 | 61 | 699.9532 | 106.472 | 436.305 | 1.569 | 60.000 | 14.232 | 13.440 | 0.000 | 23.081 | 4.184 |
| 186 | 197 | 699.9532 | 106.471 | 436.304 | 1.567 | 60.000 | 14.232 | 13.046 | 0.000 | 23.080 | 4.184 |
| 187 | 14 | 771.1717 | 107.186 | 436.517 | 1.278 | 60.000 | 13.865 | 15.185 | 0.000 | 23.072 | 4.076 |
| 188 | 70 | 771.1717 | 107.402 | 437.832 | 1.223 | 60.000 | 13.377 | 16.077 | 0.000 | 23.126 | 3.933 |
| 189 | 206 | 771.1717 | 107.400 | 437.832 | 1.222 | 60.000 | 13.377 | 15.690 | 0.000 | 23.125 | 3.933 |
| 190 | 117 | 825.2729 | 107.425 | 437.783 | 1.151 | 60.000 | 13.371 | 17.391 | 0.000 | 23.101 | 3.931 |
| 191 | 252 | 825.2729 | 107.423 | 437.783 | 1.149 | 60.000 | 13.371 | 16.986 | 0.000 | 23.100 | 3.931 |
| 192 | 9 | 954.4603 | 106.254 | 434.445 | 1.202 | 60.000 | 14.711 | 18.435 | 0.000 | 22.952 | 4.325 |
| 193 | 65 | 954.4603 | 106.420 | 435.948 | 1.147 | 60.000 | 14.111 | 19.351 | 0.000 | 23.011 | 4.149 |
| 194 | 201 | 954.4603 | 106.418 | 435.947 | 1.146 | 60.000 | 14.111 | 18.947 | 0.000 | 23.010 | 4.149 |
| 195 | 6 | 1106.2120 | 105.258 | 432.612 | 1.164 | 60.000 | 15.475 | 20.369 | 0.000 | 22.870 | 4.550 |
| 196 | 62 | 1106.2120 | 105.361 | 434.120 | 1.111 | 60.000 | 14.835 | 21.322 | 0.000 | 22.932 | 4.362 |
| 197 | 198 | 1106.2120 | 105.360 | 434.119 | 1.110 | 60.000 | 14.836 | 20.907 | 0.000 | 22.931 | 4.362 |
| 198 | 114 | 1157.0650 | 104.981 | 433.566 | 1.065 | 60.000 | 15.043 | 21.680 | 0.000 | 22.930 | 4.423 |
| 199 | 249 | 1157.0650 | 104.980 | 433.565 | 1.063 | 60.000 | 15.043 | 21.265 | 0.000 | 22.929 | 4.423 |

D.4 Lateral Maximum P_{cmd} Step Input Time Response (45% Triple Failure)

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 1 | 119 | 65.4696 | 6.348 | 58.790 | 2.708 | 18.260 | 19.417 | 17.895 | 30.000 | 5.368 | 5.709 |
| 2 | 253 | 65.4696 | 6.346 | 58.814 | 2.700 | 18.260 | 19.408 | 17.853 | 30.000 | 5.368 | 5.706 |
| 3 | 118 | 65.5666 | 6.356 | 58.018 | 2.757 | 18.288 | 19.873 | 17.958 | 30.000 | 5.377 | 5.843 |
| 4 | 122 | 67.0399 | 6.614 | 62.905 | 2.613 | 18.724 | 18.760 | 17.674 | 26.581 | 5.505 | 5.515 |
| 5 | 256 | 67.0399 | 6.612 | 62.933 | 2.604 | 18.724 | 18.751 | 17.636 | 26.506 | 5.505 | 5.513 |
| 6 | 121 | 67.4267 | 6.703 | 62.766 | 2.655 | 18.837 | 19.082 | 17.806 | 29.346 | 5.538 | 5.610 |
| 7 | 255 | 67.4267 | 6.701 | 62.794 | 2.646 | 18.837 | 19.073 | 17.767 | 29.263 | 5.538 | 5.607 |
| 8 | 124 | 67.6717 | 6.697 | 64.576 | 2.565 | 18.912 | 18.529 | 17.497 | 24.050 | 5.560 | 5.448 |
| 9 | 116 | 68.8746 | 6.977 | 62.592 | 2.825 | 19.259 | 20.000 | 18.161 | 30.000 | 5.662 | 5.975 |
| 10 | 251 | 68.8746 | 6.974 | 62.616 | 2.816 | 19.259 | 20.000 | 18.116 | 30.000 | 5.662 | 5.972 |
| 11 | 115 | 70.9929 | 7.366 | 64.944 | 3.451 | 19.880 | 20.000 | 18.259 | 30.000 | 5.845 | 6.191 |
| 12 | 10 | 74.2746 | 8.003 | 66.674 | 3.361 | 20.839 | 20.000 | 19.507 | 30.000 | 6.127 | 6.726 |
| 13 | 66 | 74.2746 | 8.054 | 71.513 | 2.831 | 20.845 | 20.000 | 18.324 | 30.000 | 6.128 | 5.961 |
| 14 | 202 | 74.2746 | 8.051 | 71.538 | 2.821 | 20.844 | 20.000 | 18.282 | 30.000 | 6.128 | 5.958 |
| 15 | 113 | 75.5664 | 8.254 | 71.208 | 3.479 | 21.222 | 20.000 | 18.361 | 30.000 | 6.239 | 6.429 |
| 16 | 250 | 77.0323 | 8.580 | 74.644 | 2.877 | 21.653 | 20.000 | 18.333 | 30.000 | 6.366 | 6.194 |
| 17 | 258 | 77.2143 | 8.522 | 79.939 | 2.440 | 21.715 | 18.896 | 17.087 | 19.620 | 6.384 | 5.556 |
| 18 | 125 | 77.2914 | 8.515 | 81.030 | 2.387 | 21.739 | 18.620 | 16.872 | 17.838 | 6.391 | 5.474 |
| 19 | 259 | 77.2914 | 8.512 | 81.061 | 2.379 | 21.739 | 18.613 | 16.847 | 17.772 | 6.391 | 5.472 |
| 20 | 37 | 80.2356 | 9.221 | 84.065 | 2.469 | 22.597 | 19.371 | 17.953 | 18.964 | 6.644 | 5.695 |
| 21 | 93 | 80.2356 | 9.363 | 87.579 | 2.387 | 22.600 | 18.209 | 17.050 | 16.524 | 6.644 | 5.354 |
| 22 | 229 | 80.2356 | 9.360 | 87.611 | 2.379 | 22.600 | 18.202 | 17.028 | 16.462 | 6.644 | 5.351 |
| 23 | 15 | 80.3692 | 9.225 | 76.780 | 2.789 | 22.628 | 20.000 | 18.978 | 30.000 | 6.653 | 6.580 |
| 24 | 71 | 80.3692 | 9.251 | 81.085 | 2.634 | 22.633 | 20.000 | 17.628 | 29.526 | 6.654 | 5.985 |
| 25 | 207 | 80.3692 | 9.248 | 81.118 | 2.626 | 22.633 | 20.000 | 17.597 | 29.444 | 6.654 | 5.981 |
| 26 | 33 | 80.5349 | 9.284 | 83.054 | 2.531 | 22.683 | 19.840 | 18.227 | 20.601 | 6.669 | 5.833 |
| 27 | 89 | 80.5349 | 9.400 | 86.603 | 2.436 | 22.687 | 18.616 | 17.213 | 18.583 | 6.670 | 5.473 |
| 28 | 225 | 80.5349 | 9.398 | 86.636 | 2.428 | 22.686 | 18.608 | 17.190 | 18.533 | 6.670 | 5.471 |
| 29 | 28 | 81.4969 | 9.533 | 83.570 | 2.589 | 22.963 | 20.000 | 18.496 | 22.750 | 6.751 | 5.938 |
| 30 | 84 | 81.4969 | 9.623 | 87.147 | 2.478 | 22.967 | 18.939 | 17.364 | 20.851 | 6.752 | 5.568 |
| 31 | 220 | 81.4969 | 9.620 | 87.178 | 2.470 | 22.967 | 18.930 | 17.339 | 20.794 | 6.752 | 5.566 |
| 32 | 1 | 82.2802 | 9.538 | 75.653 | 3.201 | 23.184 | 20.000 | 19.574 | 30.000 | 6.816 | 7.000 |
| 33 | 57 | 82.2802 | 9.538 | 80.334 | 2.885 | 23.191 | 20.000 | 18.165 | 30.000 | 6.818 | 6.722 |
| 34 | 193 | 82.2802 | 9.535 | 80.364 | 2.875 | 23.191 | 20.000 | 18.127 | 30.000 | 6.818 | 6.718 |
| 35 | 7 | 83.3181 | 9.801 | 78.664 | 2.994 | 23.489 | 20.000 | 19.570 | 30.000 | 6.906 | 7.000 |
| 36 | 63 | 83.3181 | 9.807 | 83.341 | 2.828 | 23.496 | 20.000 | 18.179 | 30.000 | 6.908 | 6.426 |
| 37 | 199 | 83.3181 | 9.804 | 83.371 | 2.819 | 23.496 | 20.000 | 18.143 | 30.000 | 6.908 | 6.422 |
| 38 | 19 | 83.4550 | 9.942 | 83.482 | 2.693 | 23.533 | 20.000 | 18.797 | 28.034 | 6.919 | 6.320 |
| 39 | 75 | 83.4550 | 9.990 | 87.626 | 2.555 | 23.538 | 19.852 | 17.495 | 25.674 | 6.920 | 5.837 |
| 40 | 211 | 83.4550 | 9.987 | 87.656 | 2.546 | 23.538 | 19.842 | 17.469 | 25.599 | 6.920 | 5.834 |
| 41 | 25 | 83.7191 | 10.052 | 85.880 | 2.633 | 23.611 | 20.000 | 18.681 | 24.865 | 6.942 | 6.083 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | δ_{amax} | δ_{amax} | δ_{rmax} | δ_{rmax} | $\delta_{elevmax}$ | $\delta_{elevmax}$ |
|----|------|-----------|---------------|-----------------|---------------|-----------------|-----------------|-----------------|-----------------|--------------------|--------------------|
| 42 | 81 | 83.7191 | 10.126 | 89.726 | 2.511 | 23.617 | 19.314 | 17.460 | 22.868 | 6.943 | 5.678 |
| 43 | 217 | 83.7191 | 10.123 | 89.756 | 2.502 | 23.616 | 19.305 | 17.435 | 22.804 | 6.943 | 5.676 |
| 44 | 34 | 87.3860 | 11.245 | 97.290 | 2.518 | 24.684 | 19.098 | 18.535 | 18.099 | 7.257 | 5.615 |
| 45 | 90 | 87.3860 | 11.369 | 100.719 | 2.407 | 24.688 | 17.978 | 17.395 | 16.941 | 7.258 | 5.286 |
| 46 | 226 | 87.3860 | 11.366 | 100.753 | 2.399 | 24.688 | 17.971 | 17.379 | 16.897 | 7.258 | 5.283 |
| 47 | 127 | 88.7159 | 11.963 | 108.774 | 2.268 | 25.081 | 16.599 | 16.600 | 13.369 | 7.374 | 4.880 |
| 48 | 261 | 88.7159 | 11.960 | 108.806 | 2.261 | 25.081 | 16.596 | 16.591 | 13.312 | 7.374 | 4.879 |
| 49 | 38 | 89.3983 | 12.127 | 104.577 | 2.458 | 25.269 | 18.058 | 18.551 | 15.253 | 7.429 | 5.309 |
| 50 | 94 | 89.3983 | 12.209 | 107.658 | 2.344 | 25.274 | 17.119 | 17.353 | 14.028 | 7.431 | 5.033 |
| 51 | 230 | 89.3983 | 12.205 | 107.691 | 2.336 | 25.274 | 17.114 | 17.344 | 13.994 | 7.431 | 5.032 |
| 52 | 11 | 91.6970 | 11.720 | 93.552 | 2.872 | 25.943 | 20.000 | 19.488 | 30.000 | 7.627 | 6.881 |
| 53 | 67 | 91.6970 | 11.711 | 97.710 | 2.687 | 25.950 | 20.000 | 17.937 | 29.919 | 7.629 | 6.287 |
| 54 | 203 | 91.6970 | 11.708 | 97.743 | 2.678 | 25.950 | 20.000 | 17.911 | 29.821 | 7.629 | 6.283 |
| 55 | 41 | 94.3473 | 13.404 | 116.605 | 2.334 | 26.725 | 17.282 | 17.498 | 13.731 | 7.857 | 5.081 |
| 56 | 97 | 94.3473 | 13.351 | 119.619 | 2.204 | 26.734 | 16.476 | 16.098 | 12.429 | 7.860 | 4.844 |
| 57 | 233 | 94.3473 | 13.348 | 119.648 | 2.197 | 26.733 | 16.474 | 16.094 | 12.377 | 7.860 | 4.843 |
| 58 | 262 | 101.0962 | 14.575 | 133.644 | 1.975 | 28.728 | 16.374 | 13.966 | 10.299 | 8.446 | 4.814 |
| 59 | 16 | 102.4478 | 14.301 | 111.231 | 2.572 | 29.085 | 20.000 | 18.163 | 25.785 | 8.551 | 6.760 |
| 60 | 72 | 102.4478 | 14.171 | 114.442 | 2.402 | 29.098 | 20.000 | 16.567 | 23.790 | 8.555 | 6.338 |
| 61 | 208 | 102.4478 | 14.167 | 114.476 | 2.404 | 29.097 | 20.000 | 16.556 | 23.712 | 8.555 | 6.334 |
| 62 | 263 | 103.7392 | 15.409 | 139.149 | 1.946 | 29.501 | 16.229 | 13.785 | 9.960 | 8.673 | 4.771 |
| 63 | 42 | 106.1299 | 16.503 | 138.765 | 2.212 | 30.177 | 17.074 | 16.577 | 12.005 | 8.872 | 5.020 |
| 64 | 98 | 106.1299 | 16.442 | 141.391 | 2.050 | 30.186 | 16.439 | 15.000 | 10.612 | 8.875 | 4.833 |
| 65 | 234 | 106.1299 | 16.442 | 141.422 | 2.044 | 30.186 | 16.438 | 15.008 | 10.573 | 8.875 | 4.833 |
| 66 | 264 | 106.4162 | 16.340 | 144.893 | 1.917 | 30.282 | 16.024 | 13.604 | 9.623 | 8.903 | 4.711 |
| 67 | 20 | 109.0025 | 16.197 | 125.746 | 2.453 | 31.000 | 20.000 | 17.852 | 21.544 | 9.114 | 6.330 |
| 68 | 76 | 109.0025 | 16.048 | 128.730 | 2.287 | 31.014 | 20.000 | 16.235 | 20.195 | 9.118 | 6.024 |
| 69 | 212 | 109.0025 | 16.044 | 128.763 | 2.279 | 31.013 | 20.000 | 16.235 | 20.137 | 9.118 | 6.021 |
| 70 | 46 | 109.1273 | 17.151 | 147.726 | 2.056 | 31.069 | 16.469 | 14.877 | 10.621 | 9.134 | 4.842 |
| 71 | 102 | 109.1273 | 17.311 | 150.567 | 1.892 | 31.073 | 15.834 | 13.401 | 9.314 | 9.136 | 4.655 |
| 72 | 238 | 109.1273 | 17.315 | 150.602 | 1.886 | 31.073 | 15.831 | 13.413 | 9.282 | 9.135 | 4.654 |
| 73 | 29 | 110.1905 | 17.318 | 136.358 | 2.371 | 31.343 | 19.153 | 17.990 | 16.911 | 9.215 | 5.631 |
| 74 | 85 | 110.1905 | 17.182 | 138.434 | 2.211 | 31.357 | 18.486 | 16.376 | 15.888 | 9.219 | 5.435 |
| 75 | 221 | 110.1905 | 17.177 | 138.457 | 2.204 | 31.356 | 18.482 | 16.383 | 15.843 | 9.219 | 5.434 |
| 76 | 8 | 110.9265 | 15.665 | 114.165 | 2.568 | 31.564 | 20.000 | 17.803 | 25.769 | 9.280 | 7.000 |
| 77 | 64 | 110.9265 | 15.486 | 116.837 | 2.393 | 31.578 | 20.000 | 16.087 | 24.068 | 9.284 | 7.000 |
| 78 | 200 | 110.9265 | 15.481 | 116.869 | 2.385 | 31.578 | 20.000 | 16.079 | 24.001 | 9.284 | 7.000 |
| 79 | 47 | 111.8726 | 18.219 | 153.546 | 2.007 | 31.867 | 16.208 | 14.626 | 10.153 | 9.369 | 4.765 |
| 80 | 103 | 111.8726 | 18.372 | 156.026 | 1.846 | 31.872 | 15.652 | 13.156 | 8.911 | 9.370 | 4.602 |
| 81 | 239 | 111.8726 | 18.377 | 156.061 | 1.840 | 31.872 | 15.650 | 13.172 | 8.882 | 9.370 | 4.601 |
| 82 | 48 | 114.6519 | 19.351 | 159.327 | 1.956 | 32.675 | 15.950 | 14.368 | 9.690 | 9.606 | 4.689 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 83 | 104 | 114.6519 | 19.507 | 161.545 | 1.799 | 32.680 | 15.449 | 12.906 | 8.513 | 9.608 | 4.542 |
| 84 | 240 | 114.6519 | 19.513 | 161.579 | 1.793 | 32.679 | 15.447 | 12.926 | 8.488 | 9.608 | 4.541 |
| 85 | 49 | 117.4653 | 20.552 | 165.078 | 1.903 | 33.491 | 15.691 | 14.105 | 9.233 | 9.846 | 4.613 |
| 86 | 105 | 117.4653 | 20.721 | 167.116 | 1.751 | 33.496 | 15.225 | 12.649 | 8.121 | 9.848 | 4.476 |
| 87 | 241 | 117.4653 | 20.727 | 167.150 | 1.745 | 33.495 | 15.224 | 12.674 | 8.099 | 9.848 | 4.476 |
| 88 | 50 | 120.3129 | 21.826 | 170.805 | 1.849 | 34.315 | 15.426 | 13.836 | 8.787 | 10.089 | 4.535 |
| 89 | 106 | 120.3129 | 22.018 | 172.729 | 1.702 | 34.320 | 14.981 | 12.385 | 7.737 | 10.090 | 4.404 |
| 90 | 242 | 120.3129 | 22.024 | 172.762 | 1.697 | 34.320 | 14.979 | 12.414 | 7.718 | 10.090 | 4.404 |
| 91 | 43 | 121.8328 | 22.031 | 170.781 | 2.041 | 34.754 | 15.940 | 15.352 | 9.954 | 10.218 | 4.686 |
| 92 | 99 | 121.8328 | 21.974 | 172.181 | 1.866 | 34.764 | 15.657 | 13.689 | 8.679 | 10.221 | 4.603 |
| 93 | 235 | 121.8328 | 21.975 | 172.206 | 1.861 | 34.764 | 15.658 | 13.717 | 8.656 | 10.221 | 4.603 |
| 94 | 51 | 123.1945 | 23.179 | 176.513 | 1.793 | 35.148 | 15.153 | 13.561 | 8.353 | 10.333 | 4.455 |
| 95 | 107 | 123.1945 | 23.002 | 177.613 | 1.660 | 35.160 | 15.002 | 12.044 | 7.376 | 10.337 | 4.411 |
| 96 | 243 | 123.1945 | 23.000 | 177.628 | 1.655 | 35.160 | 15.007 | 12.076 | 7.360 | 10.337 | 4.412 |
| 97 | 52 | 126.1103 | 24.374 | 181.721 | 1.745 | 35.993 | 15.044 | 13.263 | 7.967 | 10.582 | 4.423 |
| 98 | 108 | 126.1103 | 23.965 | 182.427 | 1.616 | 36.011 | 15.056 | 11.643 | 7.000 | 10.587 | 4.426 |
| 99 | 244 | 126.1103 | 23.963 | 182.442 | 1.611 | 36.010 | 15.060 | 11.678 | 6.987 | 10.587 | 4.428 |
| 100 | 53 | 129.0601 | 25.335 | 186.375 | 1.693 | 36.852 | 15.129 | 12.826 | 7.547 | 10.835 | 4.448 |
| 101 | 109 | 129.0601 | 24.941 | 187.245 | 1.569 | 36.871 | 15.115 | 11.187 | 6.606 | 10.840 | 4.444 |
| 102 | 245 | 129.0601 | 24.938 | 187.260 | 1.564 | 36.871 | 15.119 | 11.223 | 6.595 | 10.840 | 4.445 |
| 103 | 2 | 129.4213 | 19.958 | 133.629 | 2.339 | 36.957 | 20.000 | 16.540 | 22.278 | 10.866 | 7.000 |
| 104 | 58 | 129.4213 | 19.948 | 137.383 | 2.215 | 36.974 | 20.000 | 14.992 | 21.350 | 10.870 | 7.000 |
| 105 | 194 | 129.4213 | 19.943 | 137.415 | 2.208 | 36.974 | 20.000 | 15.002 | 21.292 | 10.870 | 7.000 |
| 106 | 17 | 129.8252 | 21.747 | 155.394 | 2.307 | 37.067 | 20.000 | 16.799 | 19.900 | 10.898 | 7.000 |
| 107 | 73 | 129.8252 | 21.690 | 158.873 | 2.161 | 37.085 | 20.000 | 15.173 | 18.982 | 10.903 | 6.411 |
| 108 | 209 | 129.8252 | 21.686 | 158.905 | 2.154 | 37.084 | 20.000 | 15.194 | 18.928 | 10.903 | 6.407 |
| 109 | 30 | 129.9582 | 23.847 | 172.563 | 2.217 | 37.092 | 18.366 | 17.266 | 14.815 | 10.905 | 5.400 |
| 110 | 86 | 129.9582 | 23.757 | 174.541 | 2.048 | 37.110 | 17.781 | 15.499 | 13.789 | 10.910 | 5.227 |
| 111 | 222 | 129.9582 | 23.751 | 174.561 | 2.042 | 37.109 | 17.780 | 15.530 | 13.746 | 10.910 | 5.227 |
| 112 | 26 | 130.0074 | 23.108 | 168.243 | 2.247 | 37.112 | 19.495 | 17.114 | 16.684 | 10.911 | 5.732 |
| 113 | 82 | 130.0074 | 23.027 | 170.158 | 2.084 | 37.130 | 18.863 | 15.392 | 15.529 | 10.916 | 5.546 |
| 114 | 218 | 130.0074 | 23.022 | 170.178 | 2.078 | 37.129 | 18.860 | 15.421 | 15.481 | 10.916 | 5.545 |
| 115 | 35 | 130.0653 | 24.599 | 177.059 | 2.170 | 37.119 | 17.322 | 17.141 | 12.905 | 10.913 | 5.093 |
| 116 | 91 | 130.0653 | 24.500 | 179.091 | 1.998 | 37.137 | 16.799 | 15.357 | 12.024 | 10.918 | 4.939 |
| 117 | 227 | 130.0653 | 24.495 | 179.111 | 1.993 | 37.136 | 16.801 | 15.392 | 11.987 | 10.918 | 4.939 |
| 118 | 21 | 130.1006 | 22.463 | 163.076 | 2.276 | 37.144 | 20.000 | 16.938 | 18.640 | 10.920 | 6.132 |
| 119 | 77 | 130.1006 | 22.393 | 165.989 | 2.119 | 37.161 | 19.984 | 15.258 | 17.393 | 10.925 | 5.875 |
| 120 | 213 | 130.1006 | 22.388 | 166.008 | 2.113 | 37.161 | 19.979 | 15.284 | 17.340 | 10.925 | 5.874 |
| 121 | 44 | 131.7744 | 26.079 | 190.060 | 1.915 | 37.641 | 15.328 | 14.472 | 8.721 | 11.066 | 4.506 |
| 122 | 100 | 131.7744 | 25.519 | 189.792 | 1.756 | 37.659 | 15.565 | 12.824 | 7.620 | 11.072 | 4.576 |
| 123 | 236 | 131.7744 | 25.516 | 189.806 | 1.751 | 37.658 | 15.569 | 12.863 | 7.605 | 11.072 | 4.577 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 124 | 54 | 132.0441 | 26.305 | 191.032 | 1.639 | 37.722 | 15.218 | 12.327 | 7.112 | 11.090 | 4.474 |
| 125 | 110 | 132.0441 | 25.928 | 192.070 | 1.518 | 37.742 | 15.181 | 10.670 | 6.194 | 11.096 | 4.463 |
| 126 | 246 | 132.0441 | 25.926 | 192.084 | 1.514 | 37.741 | 15.185 | 10.711 | 6.185 | 11.096 | 4.464 |
| 127 | 39 | 134.8266 | 26.802 | 190.762 | 2.006 | 38.516 | 16.057 | 15.480 | 9.761 | 11.324 | 4.721 |
| 128 | 95 | 134.8266 | 26.457 | 191.494 | 1.842 | 38.534 | 16.012 | 13.780 | 9.124 | 11.329 | 4.708 |
| 129 | 231 | 134.8266 | 26.454 | 191.511 | 1.837 | 38.534 | 16.017 | 13.824 | 9.094 | 11.329 | 4.709 |
| 130 | 55 | 135.0621 | 27.286 | 195.696 | 1.581 | 38.601 | 15.310 | 11.770 | 6.663 | 11.349 | 4.501 |
| 131 | 111 | 135.0621 | 26.927 | 196.904 | 1.465 | 38.622 | 15.254 | 10.098 | 5.765 | 11.355 | 4.485 |
| 132 | 247 | 135.0621 | 26.925 | 196.918 | 1.461 | 38.622 | 15.258 | 10.139 | 5.759 | 11.355 | 4.486 |
| 133 | 56 | 138.1142 | 28.277 | 200.371 | 1.522 | 39.491 | 15.405 | 11.153 | 6.200 | 11.610 | 4.529 |
| 134 | 112 | 138.1142 | 27.936 | 201.752 | 1.410 | 39.513 | 15.335 | 9.465 | 5.320 | 11.617 | 4.509 |
| 135 | 248 | 138.1142 | 27.933 | 201.765 | 1.406 | 39.513 | 15.339 | 9.509 | 5.317 | 11.617 | 4.510 |
| 136 | 45 | 167.7286 | 38.416 | 240.786 | 2.155 | 48.097 | 16.549 | 4.749 | 3.485 | 14.141 | 4.865 |
| 137 | 101 | 167.7286 | 37.892 | 242.743 | 1.992 | 48.129 | 16.602 | 3.654 | 2.856 | 14.150 | 4.881 |
| 138 | 237 | 167.7286 | 37.887 | 242.773 | 1.986 | 48.128 | 16.608 | 3.699 | 2.831 | 14.150 | 4.883 |
| 139 | 22 | 170.3164 | 37.427 | 229.638 | 3.108 | 48.779 | 20.000 | 8.400 | 11.312 | 14.341 | 6.049 |
| 140 | 78 | 170.3164 | 37.157 | 232.254 | 2.831 | 48.809 | 19.791 | 7.114 | 9.719 | 14.350 | 5.818 |
| 141 | 214 | 170.3164 | 37.150 | 232.279 | 2.821 | 48.809 | 19.788 | 7.160 | 9.668 | 14.350 | 5.818 |
| 142 | 40 | 208.2658 | 52.297 | 300.866 | 2.051 | 59.839 | 18.372 | 2.911 | 2.648 | 17.593 | 5.401 |
| 143 | 96 | 208.2658 | 51.606 | 302.760 | 1.896 | 59.888 | 18.593 | 2.170 | 1.913 | 17.607 | 5.466 |
| 144 | 232 | 208.2658 | 51.598 | 302.783 | 1.888 | 59.887 | 18.598 | 2.157 | 1.884 | 17.607 | 5.468 |
| 145 | 31 | 215.9733 | 56.828 | 312.512 | 2.609 | 60.000 | 18.148 | 5.574 | 5.756 | 18.211 | 5.335 |
| 146 | 87 | 215.9733 | 55.776 | 312.234 | 2.349 | 60.000 | 18.498 | 4.162 | 4.517 | 18.228 | 5.438 |
| 147 | 223 | 215.9733 | 55.764 | 312.247 | 2.341 | 60.000 | 18.507 | 4.233 | 4.477 | 18.228 | 5.441 |
| 148 | 126 | 222.8766 | 56.553 | 325.076 | 1.747 | 60.000 | 19.333 | 1.884 | 0.981 | 18.856 | 5.684 |
| 149 | 260 | 222.8766 | 56.543 | 325.098 | 1.740 | 60.000 | 19.337 | 1.870 | 0.953 | 18.855 | 5.685 |
| 150 | 3 | 228.5562 | 54.188 | 265.617 | 2.627 | 60.000 | 20.000 | 5.057 | 9.738 | 19.268 | 7.000 |
| 151 | 59 | 228.5562 | 53.484 | 264.458 | 2.465 | 60.000 | 20.000 | 3.800 | 8.549 | 19.286 | 7.000 |
| 152 | 195 | 228.5562 | 53.472 | 264.473 | 2.460 | 60.000 | 20.000 | 3.845 | 8.498 | 19.286 | 7.000 |
| 153 | 12 | 254.7139 | 65.990 | 323.377 | 2.538 | 60.000 | 20.000 | 4.061 | 7.367 | 21.156 | 7.000 |
| 154 | 68 | 254.7139 | 65.151 | 323.599 | 2.351 | 60.000 | 20.000 | 3.371 | 5.875 | 21.178 | 7.000 |
| 155 | 204 | 254.7139 | 65.136 | 323.612 | 2.346 | 60.000 | 20.000 | 3.368 | 5.828 | 21.178 | 7.000 |
| 156 | 36 | 264.5698 | 68.899 | 366.988 | 1.882 | 60.000 | 20.000 | 1.530 | 1.178 | 21.414 | 6.100 |
| 157 | 92 | 264.5698 | 68.071 | 369.269 | 1.745 | 60.000 | 20.000 | 1.537 | 0.391 | 21.435 | 6.003 |
| 158 | 228 | 264.5698 | 68.057 | 369.284 | 1.738 | 60.000 | 20.000 | 1.534 | 0.361 | 21.435 | 6.004 |
| 159 | 32 | 333.6127 | 78.171 | 388.904 | 1.623 | 60.000 | 20.000 | 1.429 | 0.000 | 22.727 | 7.000 |
| 160 | 88 | 333.6127 | 77.595 | 393.604 | 1.541 | 60.000 | 20.000 | 1.354 | 0.000 | 22.753 | 6.598 |
| 161 | 224 | 333.6127 | 77.581 | 393.612 | 1.537 | 60.000 | 20.000 | 1.352 | 0.000 | 22.753 | 6.597 |
| 162 | 23 | 333.8201 | 79.577 | 388.620 | 2.057 | 60.000 | 20.000 | 2.194 | 1.931 | 22.666 | 7.000 |
| 163 | 79 | 333.8201 | 78.762 | 388.749 | 1.909 | 60.000 | 20.000 | 2.203 | 0.804 | 22.695 | 7.000 |
| 164 | 215 | 333.8201 | 78.748 | 388.767 | 1.904 | 60.000 | 20.000 | 2.201 | 0.769 | 22.695 | 7.000 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 165 | 123 | 357.0172 | 80.436 | 402.505 | 1.450 | 60.000 | 20.000 | 1.248 | 0.000 | 23.208 | 6.689 |
| 166 | 257 | 357.0172 | 80.423 | 402.515 | 1.447 | 60.000 | 20.000 | 1.246 | 0.000 | 23.207 | 6.687 |
| 167 | 27 | 416.6143 | 86.467 | 407.980 | 1.454 | 60.000 | 20.000 | 1.348 | 0.000 | 23.972 | 7.000 |
| 168 | 83 | 416.6143 | 86.121 | 414.893 | 1.428 | 60.000 | 20.000 | 1.391 | 0.000 | 24.001 | 7.000 |
| 169 | 219 | 416.6143 | 86.108 | 414.912 | 1.425 | 60.000 | 20.000 | 1.390 | 0.000 | 24.001 | 7.000 |
| 170 | 13 | 499.2391 | 89.428 | 409.119 | 1.756 | 60.000 | 20.000 | 2.034 | 0.000 | 23.786 | 7.000 |
| 171 | 69 | 499.2391 | 89.054 | 409.726 | 1.685 | 60.000 | 20.000 | 2.032 | 0.000 | 23.824 | 7.000 |
| 172 | 205 | 499.2391 | 89.044 | 409.737 | 1.682 | 60.000 | 20.000 | 2.029 | 0.000 | 23.823 | 7.000 |
| 173 | 24 | 503.8640 | 89.013 | 409.922 | 1.378 | 60.000 | 20.000 | 1.326 | 0.000 | 23.873 | 7.000 |
| 174 | 80 | 503.8640 | 88.727 | 415.223 | 1.352 | 60.000 | 20.000 | 1.631 | 0.000 | 23.907 | 7.000 |
| 175 | 216 | 503.8640 | 88.716 | 415.235 | 1.349 | 60.000 | 20.000 | 1.458 | 0.000 | 23.906 | 7.000 |
| 176 | 4 | 514.2514 | 88.853 | 401.014 | 2.007 | 60.000 | 20.000 | 2.700 | 0.898 | 23.715 | 7.000 |
| 177 | 60 | 514.2514 | 88.454 | 400.424 | 1.897 | 60.000 | 20.000 | 2.661 | 0.000 | 23.757 | 7.000 |
| 178 | 196 | 514.2514 | 88.445 | 400.438 | 1.894 | 60.000 | 20.000 | 2.658 | 0.000 | 23.756 | 7.000 |
| 179 | 120 | 551.8250 | 89.597 | 416.677 | 1.243 | 60.000 | 20.000 | 2.315 | 0.000 | 23.879 | 7.000 |
| 180 | 254 | 551.8250 | 89.587 | 416.685 | 1.240 | 60.000 | 20.000 | 2.139 | 0.000 | 23.879 | 7.000 |
| 181 | 18 | 618.5337 | 90.901 | 410.958 | 1.309 | 60.000 | 20.000 | 2.667 | 0.000 | 23.755 | 7.000 |
| 182 | 74 | 618.5337 | 90.670 | 415.556 | 1.269 | 60.000 | 20.000 | 3.133 | 0.000 | 23.794 | 7.000 |
| 183 | 210 | 618.5337 | 90.662 | 415.563 | 1.267 | 60.000 | 20.000 | 2.946 | 0.000 | 23.793 | 7.000 |
| 184 | 5 | 699.9532 | 90.956 | 407.961 | 1.608 | 60.000 | 20.000 | 2.727 | 0.000 | 23.577 | 7.000 |
| 185 | 61 | 699.9532 | 90.686 | 407.721 | 1.543 | 60.000 | 20.000 | 3.349 | 0.000 | 23.625 | 7.000 |
| 186 | 197 | 699.9532 | 90.681 | 407.726 | 1.540 | 60.000 | 20.000 | 3.148 | 0.000 | 23.624 | 7.000 |
| 187 | 14 | 771.1717 | 92.011 | 410.261 | 1.224 | 60.000 | 20.000 | 4.120 | 0.000 | 23.617 | 7.000 |
| 188 | 70 | 771.1717 | 91.813 | 415.036 | 1.185 | 60.000 | 20.000 | 4.729 | 0.000 | 23.663 | 7.000 |
| 189 | 206 | 771.1717 | 91.809 | 415.041 | 1.183 | 60.000 | 20.000 | 4.527 | 0.000 | 23.662 | 7.000 |
| 190 | 117 | 825.2729 | 91.920 | 415.046 | 1.108 | 60.000 | 20.000 | 5.312 | 0.000 | 23.641 | 7.000 |
| 191 | 252 | 825.2729 | 91.916 | 415.050 | 1.106 | 60.000 | 20.000 | 5.108 | 0.000 | 23.640 | 7.000 |
| 192 | 9 | 954.4603 | 91.160 | 401.599 | 1.113 | 60.000 | 20.000 | 5.294 | 0.000 | 23.515 | 7.000 |
| 193 | 65 | 954.4603 | 90.873 | 407.777 | 1.084 | 60.000 | 20.000 | 6.059 | 0.000 | 23.565 | 7.000 |
| 194 | 201 | 954.4603 | 90.871 | 407.780 | 1.083 | 60.000 | 20.000 | 5.852 | 0.000 | 23.564 | 7.000 |
| 195 | 6 | 1106.2120 | 90.071 | 391.574 | 1.041 | 60.000 | 20.000 | 5.956 | 0.000 | 23.452 | 7.000 |
| 196 | 62 | 1106.2120 | 89.704 | 398.163 | 1.011 | 60.000 | 20.000 | 6.829 | 0.000 | 23.498 | 7.000 |
| 197 | 198 | 1106.2120 | 89.703 | 398.165 | 1.009 | 60.000 | 20.000 | 6.622 | 0.000 | 23.497 | 7.000 |
| 198 | 114 | 1157.0650 | 89.218 | 394.819 | 0.951 | 60.000 | 20.000 | 7.001 | 0.000 | 23.497 | 7.000 |
| 199 | 249 | 1157.0650 | 89.217 | 394.821 | 0.950 | 60.000 | 20.000 | 6.794 | 0.000 | 23.496 | 7.000 |

D.5 Lateral Channel Disturbance Time Response

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 1 | 119 | 65.4696 | 2.571 | 6.946 | 0.445 | 0.161 | 0.000 | 6.558 | 3.276 | 0.047 | 0.000 |
| 2 | 253 | 65.4696 | 2.569 | 6.951 | 0.444 | 0.163 | 0.000 | 6.576 | 3.269 | 0.048 | 0.000 |
| 3 | 118 | 65.5666 | 2.563 | 6.820 | 0.448 | 0.132 | 0.000 | 6.632 | 3.301 | 0.039 | 0.000 |
| 4 | 122 | 67.0399 | 2.611 | 7.198 | 0.428 | 0.242 | 0.000 | 6.341 | 3.137 | 0.071 | 0.000 |
| 5 | 256 | 67.0399 | 2.608 | 7.203 | 0.428 | 0.244 | 0.000 | 6.359 | 3.131 | 0.072 | 0.000 |
| 6 | 121 | 67.4267 | 2.624 | 7.099 | 0.433 | 0.213 | 0.000 | 6.445 | 3.171 | 0.063 | 0.000 |
| 7 | 255 | 67.4267 | 2.622 | 7.104 | 0.432 | 0.215 | 0.000 | 6.463 | 3.165 | 0.063 | 0.000 |
| 8 | 124 | 67.6717 | 2.614 | 7.297 | 0.419 | 0.282 | 0.000 | 6.210 | 3.059 | 0.083 | 0.000 |
| 9 | 116 | 68.8746 | 2.647 | 6.764 | 0.442 | 0.129 | 0.000 | 6.664 | 3.240 | 0.038 | 0.000 |
| 10 | 251 | 68.8746 | 2.644 | 6.768 | 0.441 | 0.131 | 0.000 | 6.683 | 3.233 | 0.038 | 0.000 |
| 11 | 115 | 70.9929 | 2.687 | 6.663 | 0.439 | 0.110 | 0.000 | 6.696 | 3.209 | 0.032 | 0.000 |
| 12 | 10 | 74.2746 | 2.672 | 6.570 | 0.438 | 0.122 | 0.000 | 7.142 | 3.250 | 0.036 | 0.000 |
| 13 | 66 | 74.2746 | 2.794 | 6.842 | 0.427 | 0.148 | 0.000 | 6.620 | 3.106 | 0.043 | 0.000 |
| 14 | 202 | 74.2746 | 2.792 | 6.845 | 0.426 | 0.149 | 0.000 | 6.640 | 3.099 | 0.044 | 0.000 |
| 15 | 113 | 75.5664 | 2.787 | 6.603 | 0.428 | 0.097 | 0.000 | 6.687 | 3.111 | 0.029 | 0.000 |
| 16 | 250 | 77.0323 | 2.839 | 6.727 | 0.421 | 0.120 | 0.000 | 6.664 | 3.055 | 0.035 | 0.000 |
| 17 | 258 | 77.2143 | 2.838 | 7.400 | 0.378 | 0.324 | 0.000 | 6.135 | 2.727 | 0.095 | 0.000 |
| 18 | 125 | 77.2914 | 2.839 | 7.541 | 0.370 | 0.374 | 0.000 | 6.001 | 2.662 | 0.110 | 0.000 |
| 19 | 259 | 77.2914 | 2.837 | 7.543 | 0.369 | 0.374 | 0.000 | 6.021 | 2.658 | 0.110 | 0.000 |
| 20 | 37 | 80.2356 | 2.865 | 7.446 | 0.373 | 0.365 | 0.000 | 6.426 | 2.718 | 0.107 | 0.000 |
| 21 | 93 | 80.2356 | 2.987 | 7.619 | 0.367 | 0.365 | 0.000 | 6.100 | 2.638 | 0.107 | 0.000 |
| 22 | 229 | 80.2356 | 2.984 | 7.621 | 0.367 | 0.365 | 0.000 | 6.121 | 2.634 | 0.107 | 0.000 |
| 23 | 15 | 80.3692 | 2.792 | 6.699 | 0.406 | 0.163 | 0.000 | 6.948 | 2.992 | 0.048 | 0.000 |
| 24 | 71 | 80.3692 | 2.900 | 6.892 | 0.392 | 0.169 | 0.000 | 6.443 | 2.836 | 0.050 | 0.000 |
| 25 | 207 | 80.3692 | 2.897 | 6.894 | 0.391 | 0.169 | 0.000 | 6.464 | 2.831 | 0.050 | 0.000 |
| 26 | 33 | 80.5349 | 2.857 | 7.276 | 0.381 | 0.314 | 0.000 | 6.556 | 2.781 | 0.092 | 0.000 |
| 27 | 89 | 80.5349 | 2.977 | 7.453 | 0.373 | 0.314 | 0.000 | 6.185 | 2.683 | 0.092 | 0.000 |
| 28 | 225 | 80.5349 | 2.975 | 7.454 | 0.372 | 0.314 | 0.000 | 6.205 | 2.679 | 0.092 | 0.000 |
| 29 | 28 | 81.4969 | 2.879 | 7.148 | 0.387 | 0.273 | 0.000 | 6.689 | 2.828 | 0.080 | 0.000 |
| 30 | 84 | 81.4969 | 2.996 | 7.321 | 0.377 | 0.269 | 0.000 | 6.274 | 2.712 | 0.079 | 0.000 |
| 31 | 220 | 81.4969 | 2.994 | 7.323 | 0.376 | 0.269 | 0.000 | 6.295 | 2.708 | 0.079 | 0.000 |
| 32 | 1 | 82.2802 | 2.795 | 6.386 | 0.418 | 0.087 | 0.000 | 7.155 | 3.080 | 0.026 | 0.000 |
| 33 | 57 | 82.2802 | 2.904 | 6.598 | 0.403 | 0.095 | 0.000 | 6.621 | 2.911 | 0.028 | 0.000 |
| 34 | 193 | 82.2802 | 2.902 | 6.599 | 0.402 | 0.095 | 0.000 | 6.642 | 2.905 | 0.028 | 0.000 |
| 35 | 7 | 83.3181 | 2.842 | 6.512 | 0.413 | 0.110 | 0.000 | 7.117 | 3.038 | 0.032 | 0.000 |
| 36 | 63 | 83.3181 | 2.952 | 6.713 | 0.399 | 0.113 | 0.000 | 6.596 | 2.875 | 0.033 | 0.000 |
| 37 | 199 | 83.3181 | 2.949 | 6.714 | 0.398 | 0.113 | 0.000 | 6.618 | 2.869 | 0.033 | 0.000 |
| 38 | 19 | 83.4550 | 2.888 | 6.864 | 0.392 | 0.196 | 0.000 | 6.868 | 2.874 | 0.058 | 0.000 |
| 39 | 75 | 83.4550 | 3.000 | 7.030 | 0.379 | 0.190 | 0.000 | 6.389 | 2.732 | 0.056 | 0.000 |
| 40 | 211 | 83.4550 | 2.998 | 7.031 | 0.378 | 0.190 | 0.000 | 6.410 | 2.728 | 0.056 | 0.000 |
| 41 | 25 | 83.7191 | 2.923 | 7.016 | 0.387 | 0.231 | 0.000 | 6.797 | 2.831 | 0.068 | 0.000 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 42 | 81 | 83.7191 | 3.042 | 7.181 | 0.376 | 0.222 | 0.000 | 6.347 | 2.703 | 0.065 | 0.000 |
| 43 | 217 | 83.7191 | 3.039 | 7.183 | 0.375 | 0.223 | 0.000 | 6.369 | 2.699 | 0.065 | 0.000 |
| 44 | 34 | 87.3860 | 3.138 | 7.373 | 0.372 | 0.293 | 0.000 | 6.714 | 2.700 | 0.086 | 0.000 |
| 45 | 90 | 87.3860 | 3.265 | 7.498 | 0.362 | 0.279 | 0.000 | 6.316 | 2.591 | 0.082 | 0.000 |
| 46 | 226 | 87.3860 | 3.262 | 7.499 | 0.361 | 0.280 | 0.000 | 6.339 | 2.588 | 0.082 | 0.000 |
| 47 | 127 | 88.7159 | 3.426 | 7.829 | 0.342 | 0.373 | 0.000 | 5.943 | 2.416 | 0.110 | 0.000 |
| 48 | 261 | 88.7159 | 3.423 | 7.829 | 0.341 | 0.374 | 0.000 | 5.966 | 2.414 | 0.110 | 0.000 |
| 49 | 38 | 89.3983 | 3.307 | 7.585 | 0.366 | 0.332 | 0.000 | 6.741 | 2.649 | 0.098 | 0.000 |
| 50 | 94 | 89.3983 | 3.419 | 7.670 | 0.354 | 0.319 | 0.000 | 6.307 | 2.528 | 0.094 | 0.000 |
| 51 | 230 | 89.3983 | 3.416 | 7.670 | 0.354 | 0.320 | 0.000 | 6.331 | 2.525 | 0.094 | 0.000 |
| 52 | 11 | 91.6970 | 3.048 | 6.691 | 0.387 | 0.126 | 0.000 | 7.063 | 2.815 | 0.037 | 0.000 |
| 53 | 67 | 91.6970 | 3.144 | 6.806 | 0.371 | 0.115 | 0.000 | 6.535 | 2.651 | 0.034 | 0.000 |
| 54 | 203 | 91.6970 | 3.141 | 6.806 | 0.370 | 0.115 | 0.000 | 6.558 | 2.646 | 0.034 | 0.000 |
| 55 | 41 | 94.3473 | 3.483 | 7.659 | 0.336 | 0.349 | 0.000 | 6.169 | 2.396 | 0.103 | 0.000 |
| 56 | 97 | 94.3473 | 3.570 | 7.709 | 0.321 | 0.402 | 0.000 | 5.675 | 2.243 | 0.118 | 0.000 |
| 57 | 233 | 94.3473 | 3.568 | 7.709 | 0.321 | 0.401 | 0.000 | 5.699 | 2.242 | 0.118 | 0.000 |
| 58 | 262 | 101.0962 | 3.705 | 7.722 | 0.274 | 0.491 | 0.000 | 4.839 | 1.858 | 0.144 | 0.000 |
| 59 | 16 | 102.4478 | 3.243 | 6.655 | 0.339 | 0.113 | 0.000 | 6.648 | 2.452 | 0.033 | 0.000 |
| 60 | 72 | 102.4478 | 3.312 | 6.708 | 0.322 | 0.109 | 0.000 | 6.060 | 2.286 | 0.032 | 0.000 |
| 61 | 208 | 102.4478 | 3.310 | 6.707 | 0.321 | 0.109 | 0.000 | 6.085 | 2.284 | 0.032 | 0.000 |
| 62 | 263 | 103.7392 | 3.819 | 7.682 | 0.269 | 0.503 | 0.000 | 4.802 | 1.817 | 0.148 | 0.000 |
| 63 | 42 | 106.1299 | 3.776 | 7.431 | 0.300 | 0.366 | 0.000 | 5.694 | 2.095 | 0.108 | 0.000 |
| 64 | 98 | 106.1299 | 3.863 | 7.435 | 0.283 | 0.434 | 0.000 | 5.231 | 1.943 | 0.128 | 0.000 |
| 65 | 234 | 106.1299 | 3.861 | 7.434 | 0.283 | 0.433 | 0.000 | 5.257 | 1.943 | 0.127 | 0.000 |
| 66 | 264 | 106.4162 | 3.950 | 7.634 | 0.264 | 0.515 | 0.000 | 4.779 | 1.782 | 0.152 | 0.000 |
| 67 | 20 | 109.0025 | 3.428 | 6.718 | 0.319 | 0.123 | 0.000 | 6.448 | 2.292 | 0.036 | 0.000 |
| 68 | 76 | 109.0025 | 3.491 | 6.741 | 0.303 | 0.149 | 0.000 | 5.882 | 2.135 | 0.044 | 0.000 |
| 69 | 212 | 109.0025 | 3.489 | 6.739 | 0.302 | 0.148 | 0.000 | 5.908 | 2.134 | 0.043 | 0.000 |
| 70 | 46 | 109.1273 | 3.952 | 7.579 | 0.273 | 0.462 | 0.000 | 5.082 | 1.864 | 0.136 | 0.000 |
| 71 | 102 | 109.1273 | 4.084 | 7.578 | 0.260 | 0.524 | 0.000 | 4.730 | 1.746 | 0.154 | 0.000 |
| 72 | 238 | 109.1273 | 4.083 | 7.577 | 0.260 | 0.524 | 0.000 | 4.757 | 1.747 | 0.154 | 0.000 |
| 73 | 29 | 110.1905 | 3.639 | 6.935 | 0.315 | 0.193 | 0.000 | 6.376 | 2.253 | 0.057 | 0.000 |
| 74 | 85 | 110.1905 | 3.707 | 6.938 | 0.298 | 0.244 | 0.000 | 5.839 | 2.097 | 0.072 | 0.000 |
| 75 | 221 | 110.1905 | 3.705 | 6.936 | 0.298 | 0.242 | 0.000 | 5.866 | 2.096 | 0.071 | 0.000 |
| 76 | 8 | 110.9265 | 3.225 | 6.361 | 0.319 | 0.059 | 0.000 | 6.572 | 2.297 | 0.017 | 0.000 |
| 77 | 64 | 110.9265 | 3.277 | 6.391 | 0.302 | 0.056 | 0.000 | 5.959 | 2.134 | 0.016 | 0.000 |
| 78 | 200 | 110.9265 | 3.275 | 6.390 | 0.301 | 0.056 | 0.000 | 5.985 | 2.132 | 0.016 | 0.000 |
| 79 | 47 | 111.8726 | 4.081 | 7.496 | 0.269 | 0.465 | 0.000 | 5.062 | 1.830 | 0.137 | 0.000 |
| 80 | 103 | 111.8726 | 4.207 | 7.484 | 0.255 | 0.521 | 0.000 | 4.711 | 1.714 | 0.153 | 0.000 |
| 81 | 239 | 111.8726 | 4.207 | 7.482 | 0.255 | 0.520 | 0.000 | 4.738 | 1.715 | 0.153 | 0.000 |
| 82 | 48 | 114.6519 | 4.213 | 7.410 | 0.264 | 0.464 | 0.000 | 5.047 | 1.797 | 0.137 | 0.000 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 83 | 104 | 114.6519 | 4.339 | 7.389 | 0.251 | 0.516 | 0.000 | 4.694 | 1.683 | 0.152 | 0.000 |
| 84 | 240 | 114.6519 | 4.338 | 7.387 | 0.250 | 0.516 | 0.000 | 4.722 | 1.685 | 0.152 | 0.000 |
| 85 | 49 | 117.4653 | 4.349 | 7.321 | 0.259 | 0.462 | 0.000 | 5.036 | 1.764 | 0.136 | 0.000 |
| 86 | 105 | 117.4653 | 4.477 | 7.291 | 0.246 | 0.511 | 0.000 | 4.678 | 1.653 | 0.150 | 0.000 |
| 87 | 241 | 117.4653 | 4.476 | 7.289 | 0.246 | 0.511 | 0.000 | 4.707 | 1.654 | 0.150 | 0.000 |
| 88 | 50 | 120.3129 | 4.488 | 7.231 | 0.254 | 0.458 | 0.000 | 5.025 | 1.730 | 0.135 | 0.000 |
| 89 | 106 | 120.3129 | 4.623 | 7.193 | 0.242 | 0.504 | 0.000 | 4.662 | 1.621 | 0.148 | 0.000 |
| 90 | 242 | 120.3129 | 4.622 | 7.190 | 0.241 | 0.504 | 0.000 | 4.692 | 1.623 | 0.148 | 0.000 |
| 91 | 43 | 121.8328 | 4.408 | 7.114 | 0.268 | 0.420 | 0.000 | 5.372 | 1.838 | 0.124 | 0.000 |
| 92 | 99 | 121.8328 | 4.479 | 7.080 | 0.252 | 0.464 | 0.000 | 4.944 | 1.706 | 0.136 | 0.000 |
| 93 | 235 | 121.8328 | 4.477 | 7.078 | 0.252 | 0.464 | 0.000 | 4.973 | 1.707 | 0.136 | 0.000 |
| 94 | 51 | 123.1945 | 4.631 | 7.140 | 0.249 | 0.451 | 0.000 | 5.016 | 1.697 | 0.133 | 0.000 |
| 95 | 107 | 123.1945 | 4.692 | 7.102 | 0.235 | 0.492 | 0.000 | 4.590 | 1.579 | 0.145 | 0.000 |
| 96 | 243 | 123.1945 | 4.689 | 7.099 | 0.235 | 0.492 | 0.000 | 4.619 | 1.580 | 0.145 | 0.000 |
| 97 | 52 | 126.1103 | 4.729 | 7.055 | 0.244 | 0.440 | 0.000 | 4.977 | 1.659 | 0.129 | 0.000 |
| 98 | 108 | 126.1103 | 4.752 | 7.013 | 0.229 | 0.479 | 0.000 | 4.502 | 1.533 | 0.141 | 0.000 |
| 99 | 244 | 126.1103 | 4.749 | 7.010 | 0.229 | 0.480 | 0.000 | 4.531 | 1.534 | 0.141 | 0.000 |
| 100 | 53 | 129.0601 | 4.772 | 6.974 | 0.237 | 0.424 | 0.000 | 4.881 | 1.608 | 0.125 | 0.000 |
| 101 | 109 | 129.0601 | 4.811 | 6.927 | 0.222 | 0.466 | 0.000 | 4.402 | 1.485 | 0.137 | 0.000 |
| 102 | 245 | 129.0601 | 4.809 | 6.924 | 0.222 | 0.467 | 0.000 | 4.432 | 1.486 | 0.137 | 0.000 |
| 103 | 2 | 129.4213 | 3.445 | 6.179 | 0.277 | 0.029 | 0.000 | 6.164 | 1.969 | 0.009 | 0.000 |
| 104 | 58 | 129.4213 | 3.528 | 6.214 | 0.265 | 0.041 | 0.000 | 5.624 | 1.856 | 0.012 | 0.000 |
| 105 | 194 | 129.4213 | 3.526 | 6.213 | 0.265 | 0.040 | 0.000 | 5.653 | 1.855 | 0.012 | 0.000 |
| 106 | 17 | 129.8252 | 3.757 | 6.414 | 0.277 | 0.101 | 0.000 | 6.075 | 1.963 | 0.030 | 0.000 |
| 107 | 73 | 129.8252 | 3.840 | 6.428 | 0.264 | 0.135 | 0.000 | 5.550 | 1.841 | 0.040 | 0.000 |
| 108 | 209 | 129.8252 | 3.837 | 6.426 | 0.263 | 0.134 | 0.000 | 5.581 | 1.840 | 0.039 | 0.000 |
| 109 | 30 | 129.9582 | 4.126 | 6.610 | 0.278 | 0.223 | 0.000 | 6.056 | 1.967 | 0.066 | 0.000 |
| 110 | 86 | 129.9582 | 4.217 | 6.590 | 0.263 | 0.273 | 0.000 | 5.545 | 1.826 | 0.080 | 0.000 |
| 111 | 222 | 129.9582 | 4.214 | 6.588 | 0.262 | 0.272 | 0.000 | 5.577 | 1.827 | 0.080 | 0.000 |
| 112 | 26 | 130.0074 | 3.996 | 6.556 | 0.278 | 0.178 | 0.000 | 6.061 | 1.966 | 0.052 | 0.000 |
| 113 | 82 | 130.0074 | 4.083 | 6.549 | 0.263 | 0.222 | 0.000 | 5.544 | 1.832 | 0.065 | 0.000 |
| 114 | 218 | 130.0074 | 4.080 | 6.547 | 0.263 | 0.222 | 0.000 | 5.576 | 1.832 | 0.065 | 0.000 |
| 115 | 35 | 130.0653 | 4.265 | 6.651 | 0.276 | 0.271 | 0.000 | 5.981 | 1.946 | 0.080 | 0.000 |
| 116 | 91 | 130.0653 | 4.360 | 6.616 | 0.260 | 0.327 | 0.000 | 5.482 | 1.801 | 0.096 | 0.000 |
| 117 | 227 | 130.0653 | 4.357 | 6.614 | 0.259 | 0.326 | 0.000 | 5.515 | 1.802 | 0.096 | 0.000 |
| 118 | 21 | 130.1006 | 3.877 | 6.488 | 0.277 | 0.137 | 0.000 | 6.064 | 1.962 | 0.040 | 0.000 |
| 119 | 77 | 130.1006 | 3.961 | 6.491 | 0.263 | 0.176 | 0.000 | 5.542 | 1.834 | 0.052 | 0.000 |
| 120 | 213 | 130.1006 | 3.959 | 6.489 | 0.263 | 0.175 | 0.000 | 5.573 | 1.834 | 0.052 | 0.000 |
| 121 | 44 | 131.7744 | 4.828 | 6.866 | 0.251 | 0.426 | 0.000 | 5.221 | 1.703 | 0.125 | 0.000 |
| 122 | 100 | 131.7744 | 4.778 | 6.853 | 0.234 | 0.449 | 0.000 | 4.771 | 1.574 | 0.132 | 0.000 |
| 123 | 236 | 131.7744 | 4.775 | 6.850 | 0.234 | 0.450 | 0.000 | 4.803 | 1.576 | 0.132 | 0.000 |

| # | srf# | \bar{q} | ϕ_{1sec} | $\phi_{2.8sec}$ | β_{max} | $\delta_{a_{max}}$ | $\delta_{a_{max}}$ | $\delta_{r_{max}}$ | $\delta_{r_{max}}$ | $\delta_{elev_{max}}$ | $\delta_{elev_{max}}$ |
|-----|------|-----------|---------------|-----------------|---------------|--------------------|--------------------|--------------------|--------------------|-----------------------|-----------------------|
| 124 | 54 | 132.0441 | 4.813 | 6.895 | 0.229 | 0.407 | 0.000 | 4.771 | 1.555 | 0.120 | 0.000 |
| 125 | 110 | 132.0441 | 4.870 | 6.843 | 0.215 | 0.453 | 0.000 | 4.290 | 1.434 | 0.133 | 0.000 |
| 126 | 246 | 132.0441 | 4.867 | 6.840 | 0.215 | 0.454 | 0.000 | 4.321 | 1.436 | 0.133 | 0.000 |
| 127 | 39 | 134.8266 | 4.656 | 6.690 | 0.257 | 0.347 | 0.000 | 5.501 | 1.774 | 0.102 | 0.000 |
| 128 | 95 | 134.8266 | 4.678 | 6.660 | 0.241 | 0.387 | 0.000 | 5.047 | 1.643 | 0.114 | 0.000 |
| 129 | 231 | 134.8266 | 4.675 | 6.658 | 0.241 | 0.387 | 0.000 | 5.081 | 1.645 | 0.114 | 0.000 |
| 130 | 55 | 135.0621 | 4.854 | 6.818 | 0.221 | 0.391 | 0.000 | 4.648 | 1.500 | 0.115 | 0.000 |
| 131 | 111 | 135.0621 | 4.929 | 6.761 | 0.208 | 0.440 | 0.000 | 4.166 | 1.382 | 0.129 | 0.000 |
| 132 | 247 | 135.0621 | 4.926 | 6.759 | 0.208 | 0.441 | 0.000 | 4.197 | 1.384 | 0.130 | 0.000 |
| 133 | 56 | 138.1142 | 4.894 | 6.744 | 0.213 | 0.374 | 0.000 | 4.511 | 1.444 | 0.110 | 0.000 |
| 134 | 112 | 138.1142 | 4.987 | 6.683 | 0.201 | 0.427 | 0.000 | 4.030 | 1.328 | 0.126 | 0.000 |
| 135 | 248 | 138.1142 | 4.984 | 6.680 | 0.200 | 0.429 | 0.000 | 4.060 | 1.330 | 0.126 | 0.000 |
| 136 | 45 | 167.7286 | 5.207 | 6.327 | 0.253 | 0.180 | 0.000 | 2.364 | 0.843 | 0.053 | 0.000 |
| 137 | 101 | 167.7286 | 5.303 | 6.288 | 0.239 | 0.191 | 0.000 | 2.116 | 0.772 | 0.056 | 0.000 |
| 138 | 237 | 167.7286 | 5.299 | 6.286 | 0.239 | 0.193 | 0.000 | 2.139 | 0.774 | 0.057 | 0.000 |
| 139 | 22 | 170.3164 | 4.648 | 6.084 | 0.311 | 0.113 | 0.000 | 3.238 | 1.096 | 0.033 | 0.000 |
| 140 | 78 | 170.3164 | 4.720 | 6.092 | 0.294 | 0.143 | 0.000 | 2.973 | 1.009 | 0.042 | 0.000 |
| 141 | 214 | 170.3164 | 4.716 | 6.090 | 0.294 | 0.143 | 0.000 | 2.999 | 1.010 | 0.042 | 0.000 |
| 142 | 40 | 208.2658 | 5.401 | 6.049 | 0.220 | 0.074 | 0.000 | 2.208 | 0.732 | 0.022 | 0.000 |
| 143 | 96 | 208.2658 | 5.511 | 6.027 | 0.208 | 0.137 | 0.000 | 1.976 | 0.668 | 0.040 | 0.000 |
| 144 | 232 | 208.2658 | 5.507 | 6.024 | 0.207 | 0.134 | 0.000 | 2.002 | 0.669 | 0.039 | 0.000 |
| 145 | 31 | 215.9733 | 5.414 | 5.970 | 0.256 | 0.080 | 0.000 | 2.856 | 0.880 | 0.023 | 0.000 |
| 146 | 87 | 215.9733 | 5.401 | 5.943 | 0.238 | 0.103 | 0.000 | 2.575 | 0.798 | 0.030 | 0.000 |
| 147 | 223 | 215.9733 | 5.398 | 5.940 | 0.238 | 0.105 | 0.000 | 2.605 | 0.800 | 0.031 | 0.000 |
| 148 | 126 | 222.8766 | 5.593 | 5.964 | 0.191 | 0.195 | 0.000 | 1.804 | 0.658 | 0.057 | 0.000 |
| 149 | 260 | 222.8766 | 5.589 | 5.961 | 0.191 | 0.192 | 0.000 | 1.829 | 0.658 | 0.056 | 0.000 |
| 150 | 3 | 228.5562 | 4.803 | 5.916 | 0.261 | 0.024 | 0.000 | 3.091 | 1.016 | 0.007 | 0.000 |
| 151 | 59 | 228.5562 | 4.799 | 5.896 | 0.249 | 0.029 | 0.000 | 2.804 | 1.009 | 0.009 | 0.000 |
| 152 | 195 | 228.5562 | 4.796 | 5.894 | 0.249 | 0.029 | 0.000 | 2.833 | 1.008 | 0.009 | 0.000 |
| 153 | 12 | 254.7139 | 5.057 | 5.807 | 0.242 | 0.026 | 0.000 | 2.993 | 0.938 | 0.008 | 0.000 |
| 154 | 68 | 254.7139 | 5.084 | 5.798 | 0.227 | 0.040 | 0.000 | 2.704 | 0.925 | 0.012 | 0.000 |
| 155 | 204 | 254.7139 | 5.081 | 5.797 | 0.227 | 0.041 | 0.000 | 2.736 | 0.925 | 0.012 | 0.000 |
| 156 | 36 | 264.5698 | 5.483 | 5.892 | 0.188 | 0.132 | 0.000 | 2.031 | 0.675 | 0.039 | 0.000 |
| 157 | 92 | 264.5698 | 5.640 | 5.902 | 0.178 | 0.192 | 0.000 | 1.807 | 0.669 | 0.056 | 0.000 |
| 158 | 228 | 264.5698 | 5.637 | 5.899 | 0.177 | 0.190 | 0.000 | 1.835 | 0.668 | 0.056 | 0.000 |
| 159 | 32 | 333.6127 | 5.488 | 5.823 | 0.165 | 0.144 | 0.000 | 1.906 | 0.677 | 0.042 | 0.000 |
| 160 | 88 | 333.6127 | 5.678 | 5.864 | 0.156 | 0.187 | 0.000 | 1.693 | 0.670 | 0.055 | 0.000 |
| 161 | 224 | 333.6127 | 5.675 | 5.863 | 0.156 | 0.186 | 0.000 | 1.721 | 0.670 | 0.055 | 0.000 |
| 162 | 23 | 333.8201 | 5.424 | 5.794 | 0.192 | 0.037 | 0.000 | 2.476 | 0.790 | 0.011 | 0.000 |
| 163 | 79 | 333.8201 | 5.460 | 5.787 | 0.181 | 0.061 | 0.000 | 2.225 | 0.780 | 0.018 | 0.000 |
| 164 | 215 | 333.8201 | 5.458 | 5.785 | 0.180 | 0.060 | 0.000 | 2.257 | 0.780 | 0.018 | 0.000 |

Appendix E. Matlab's "Linmod" Function

Phillips employed *Matlab's* "linmod" macro to generate the C^*/δ_e transfer function in the longitudinal design and to close the dutch roll damper loop in the lateral/directional design. In this research some problems were identified with linmod after the C^*/δ_e transfer functions used in Phillips' research did not match those generated in this design for the same plant sets. Phillips' functions had spurious feedforward terms and zeros in the extreme left half plane not found when C^* was generated via matrix manipulation. These discrepancies prompted an investigation of the entire transfer function generation scheme employed in the two designs. The only difference in the algorithms stemmed from the generation of C^* . Assuming that the linmod function was simply written incorrectly, the longitudinal design proceeded without it. However in the lateral channel Phillips' models matched identically to those generated via matrix manipulation, so the problem was more involved than originally assumed. It appears after analyzing the linmod function that the addition of a nonlinear weighting scheme (Fig 5.2) in the longitudinal design caused linmod to produce the incorrect C^* transfer functions.

To understand the ramifications of these incorrect transfer functions on Phillips' design, his compensator was loaded into QFTCAD along with the correct longitudinal transfer functions. Fortunately the additional zeros introduced by linmod, only mildly effected Phillips' design. From the stability validation plot found in Fig. E.1, Phillips' compensator maintained the required stability margin for all plant cases except those high \bar{q} plants (above 700 (lbs/ft²)).

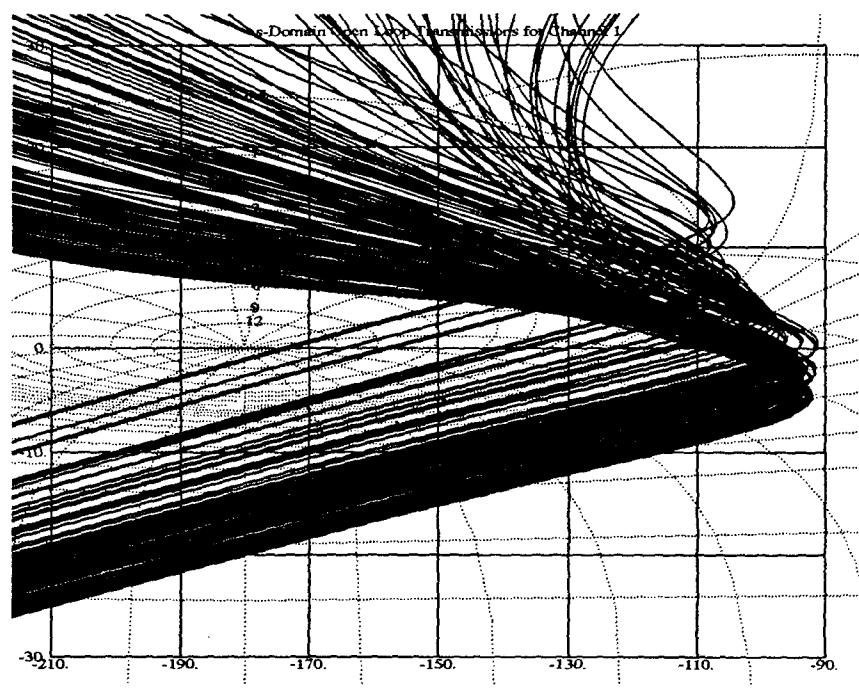


Figure E.1 Phillips' Compensated system Stability Validation

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Vita

Vincent Joseph Caciatoe [REDACTED]

[REDACTED] Though he spent 6 years in Boston's South Shore area, Pennsylvania has always been called home. With astronaut aspirations, he decided to pursue a Bachelors degree in Electrical Engineering Engineering. Vincent matriculated into Lehigh University in 1990 and received a 4 year AFROTC scholarship to finance the experience. Earning a B.S.E.E degree with honors and his commission as a Second Lieutenant in the United States Air Force, he was selected to attend the Air Force Institute of Technology for his first assignment. Upon completion of a Masters of Science degree in Electrical Engineering, Vincent will proceed to Phillips Lab, Kirkland AFB, New Mexico. Vincent is a member of Tau Beta Pi, Omicron Delta Kappa and an Eagle Scout.

Permanent address: 25 Longview Road
Glen Mills, PA 19342

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| 6. AUTHOR(S) Vincent J. Caciatoe Second Lieutenant, USAF | | | | | | |
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| 14. SUBJECT TERMS Quantitative Feedback Theory, QFT, FCS, VISTA, F-16, Subsonic Envelope, Configuration Variation, Failure Modeling | | | | 15. NUMBER OF PAGES 224 | | |
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